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ENERGY ANALYSIS HANDBOOK FOR PREPARATION OF OIL SHALE DEVELOPMENT ENVIRONMENTAL IMPACT STATEMENTS

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COLORADO STATE OFFICE

U.S. BUREAU OF LAND MANAGEMENT

DENVER, COLORADO

By

ALBERT G. MELCHER, P.E., PROJECT MANAGER
ROBERT L. GRIFFIS, PROJECT ENGINEER
RONALD GIST, PROJECT ENGINEER
CHRIS COX, SENIOR PROJECT ENGINEER

March, 1982

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COLORADO SCHOOL OF MINES RESEARCH INSTITUTE
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ABSTRACT

Net energy analysis is a methodology of determining how much energy is required to produce energy. The Bureau of Land Management, U.S. Department of the Interior, addresses this subject in Environmental Impact Statements dealing with energy production. This handbook provides a methodology and data for the subject for various scenarios or projects of oil shale development. Also, data are provided for competetive or conventional energy production systems.

The handbook includes: (1) a general discussion of net energy analysis and various aspects of it which can be dealt with in different ways; (2) a general methodology; (3) data on oil shale production processes such as mining, retorting by various means, upgrading, etc., for use with the methodology; (4) an illustrative set of calculations using the data with the methodology; (5) data on other energy systems for net energy analyis. The processes which are involved in oil shale and other energy production are briefly described, and assumptions on data are given.

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1. MANAGEMENT SUMMARY

The requirements of the National Environmental Policy Act (NEPA), and the Guidelines of the Council on Environmental Quality (CEQ) which implement the Act, require that energy consumption and conservation must be addressed and considered in Environmental Impact Statements (EIS). The energy analysis methodology which developed in the early 1970's, and which has become known as "Net Energy Analysis", is an especially appropriate methodology to use in complying with CEQ Guidelines. It has several virtues for this purpose:

- o It can address different types of energy systems with consistent logic and data;
- o It can deal with production, conversion and consumption of energy;
- o It is flexible so that it can be responsive to different issues;
- o It is not so complex that it is difficult to use, especially if the user does not have a higher education specialty in physics or chemistry;
- o It does not need sophisticated computer modeling;
- o It can be presented graphically and numerically so that lay persons can interpret it.

A lead Federal agency must prepare an Environmental Impact Statement (EIS) on many proposed developments which will produce energy or convert it from one form to another. Net energy analysis, analyzing all the energy inputs and outputs, is becoming an accepted approach for use in EIS's. The approach developed for the Bureau of Land Management, and presented in this handbook, has been utilized in a number of studies, including several for Department of the Interior EIS's.

The term "net energy" means simply the usable yield of energy from any system which produces energy or converts energy from one form to another. The entire system requires that more energy be put into the system than is eventually yielded in usable form. The "gross energy" would include both the final usable energy as well as all the other energy which is put into, or invested in the sdystem to make it operate, but which does not become part of the final usable product.

Net energy yields of an energy-producing system can be compared to all the inputs into the system, such as purchased fuels and electricity, materials for construction of the system, and energy used by the people involved in its construction and operation.

Aspects of net energy analysis which must be understood prior to undertaking a study are:

(1) Net Energy Analysis: General Considerations

- Energy Inputs and Outputs of a System
- System Boundary Considerations
- Energy Issues and Accounting Methods
- Energy Quality
- Time Periods
- Regional and Site-Specific Analyses

(2) Uses of Net Energy Analysis

(3) Data for Net Energy Analysis

- Level of Detail
- Quality and Accuracy of Data
- Generality or Specificity of Processes
- Data Sources

(4) Computational Approaches

- The General Approach
- Materials Computational Approaches

(5) Presentation of Analytical Results

All of these are discussed in this handbook.

A general methodology is presented. In the simpliest terms, only major steps are needed:

(1) Describe the major elements of an entire system, called a "trajectory", of bringing resources into the marketplace as energy products;

(2) For each of these elements, called "modules", describe and quantify all the inputs and outputs of the element;

(3) Total the data for all the elements in the trajectory to get the system inputs and outputs.

The handbook describes this process in greater detail. It then presents a description of all the elements of alternative oil shale production systems. For each element, the best available data is presented. The element processes and analytical/data assumptions are presented so that the user of the handbook can understand the CSMRI approach to the element.

Next, one illustrative examples of oil shale production system is worked out in the handbook. It consists of a surface oil shale mine, with raw shale conveyed to a direct-heated gas flow surface retort, and with the shale oil upgraded and transported to a refinery. The example assumes that there will be an on-site electric power plant.

Finally, the handbook contains module descriptions and data for a variety of energy production processes which compare or compete with oil shale production.

2. INTRODUCTION

2.1 NET ENERGY ANALYSIS

The requirements of the National Environmental Policy Act (NEPA), and the Guidelines of the Council on Environmental Quality (CEQ) which implement the Act, require that energy consumption and conservation must be addressed and considered in Environmental Impact Statements (EIS). The energy analysis methodology which developed in the early 1970's, and which has become known as "Net Energy Analysis", is an especially appropriate methodology to use in complying with CEQ Guidelines. It has several virtues for this purpose:

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- It can deal with production, conversion and consumption of energy;
- It is flexible so that it can be responsive to different issues;
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The term "net energy" means simply the usable yield of energy from any system which produces energy or converts energy from one form to another. The entire system requires that more energy be put into the system than is eventually yielded in usable form. The "gross energy" would include both the final usable energy as well as all the other energy which is put into, or invested in the system to make it operate, but which does not become part of the final usable product.

2.1.1 Energy Inputs and Outputs of a System

The subject of energy inputs and outputs, addressing the question of "how much energy does it take to produce energy," is known as net energy analysis. The subject gained prominence in the 1970's as it became evident that America had serious energy problems and that new tools and analytical techniques were needed to deal with the subject of energy. Net energy analysis is one of these new analytical techniques. Practitioners of net energy analysis initially explored a variety of methodologies, but some of these have been abandoned.

Now, there is general concurrence in the general methodology used in this handbook. This is evidenced by the findings of the comparative analysis of net energy analysis methodologies funded by the Department of Energy (DOE). The recommendations of the researchers of that DOE project are, in general, met by the methodology used here.

This method was originally developed in a study entitled "Net Energy Analysis: An Energy Balance Study of Fossil Energy Resources" done under the auspices of the Colorado Energy Research Institute (CERI) of the Colorado School of Mines. The first part of that study dealt with the problem of methodology development. The second part involved data acquisition for a variety of system components in the processes of extracting, transporting, converting, and delivering various forms of energy to end users. The third part of the study analyzed these data to determine the net energy of 20 different systems of fossil energy production (such as coal to gasoline, oil shale to electricity, etc.). The authors of this handbook have subsequently utilized this method of other studies on net energy in energy and materials production systems, involving oil shale, coal mining, coal-electric systems, and materials production.

Net energy analysis is a flexible tool. It can deal with the energy inputs and outputs of simple unit operations or long and complex chains of units in energy or materials production systems. It can also deal with different types or groups of inputs and outputs. The length and breadth of the system and the energy flows included or excluded from the analysis define a boundary for the study. Net energy analysis is a model of a real system and, as in all models, simplifications of the real world are needed. The definition of the system boundary is the primary and major simplification in structuring the net energy model. Therefore, for any specific net energy study, early consideration must be given to the boundary of this study, to how much of the entire energy system should be examined.

First of all, consider a very simple system, such as a natural gas-fired home furnace. This can be considered as a simple operation, with natural gas and air mixed in a combustion chamber, heated to ignition, and the gas burned. The heat of combustion is transferred to air is a segregated chamber, which is then circulated throughout the house. The direct inputs into the system consist of the natural gas and air necessary for combustion (oxidization) of the gas; the output consists of heat carried (convected) by the circulating air. However, other factors are needed. The combustion and hot air chambers must be made of materials, such as steel, which required energy in their production. If an electric fan is used to circulate air or force air into the combustion chamber, as it common, electricity is also required to make the system work.

The furnace can be considered as a single "module" or major energy operation. It is important to note that, in any operation involving energy, some of the energy being operated on becomes unusable; it is in effect "lost". In the case of the furnace, some heat goes up the flue and is emitted without being transferred to the circulating air which warms the house.

Figure 2.1a shows the concept of a module with inputs, outputs and losses. Considering the furnace, the natural gas is the input from the left, called "Principal Energy". The hot air is the output to the right, called "Energy

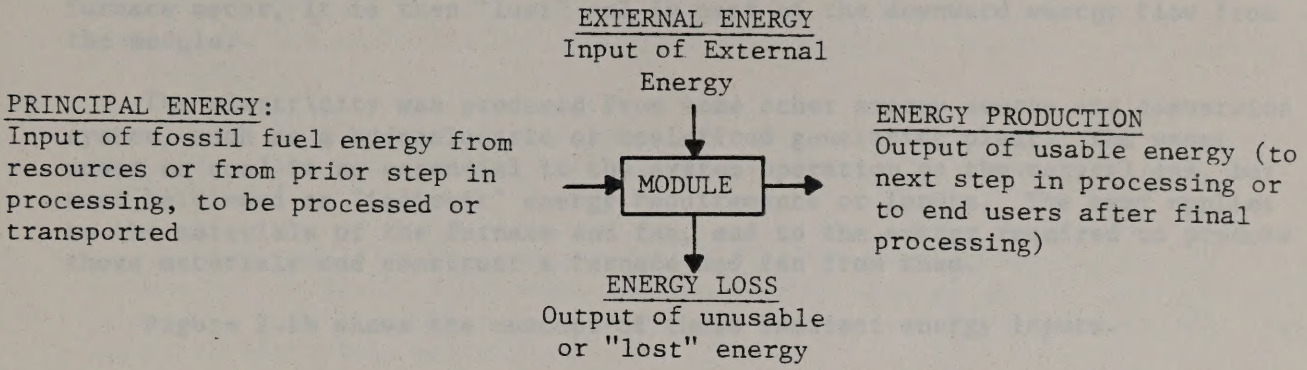

EXTERNAL ENERGY
Input of External Energy
PRINCIPAL ENERGY:
Input of fossil fuel energy from resources or from prior step in processing, to be processed or transported
MODULE
ENERGY PRODUCTION
Output of usable energy (to next step in processing or to end users after final processing)
ENERGY LOSS
Output of unusable or "lost" energy

FIGURE 2.1a
A "Module" in Producing Fossil Fuel Energy

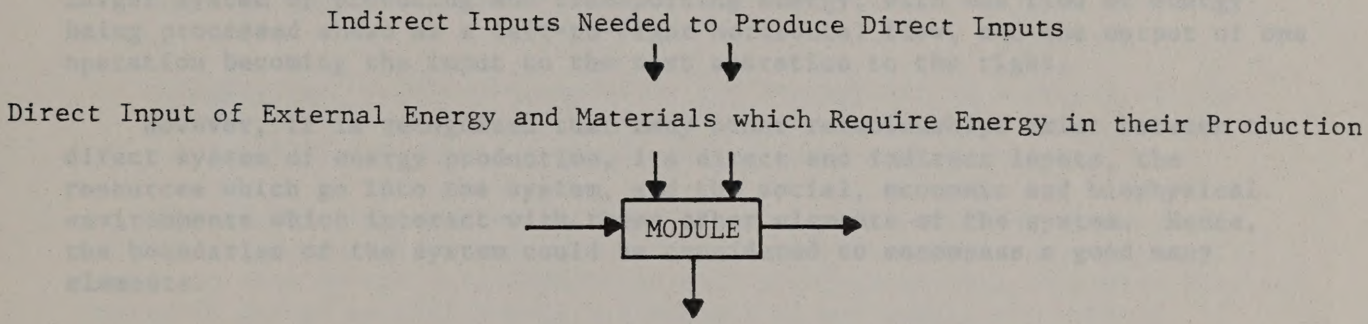

Indirect Inputs Needed to Produce Direct Inputs
Direct Input of External Energy and Materials which Require Energy in their Production
MODULE

FIGURE 2.1b
Module Showing Concept of Direct and Indirect External Energy

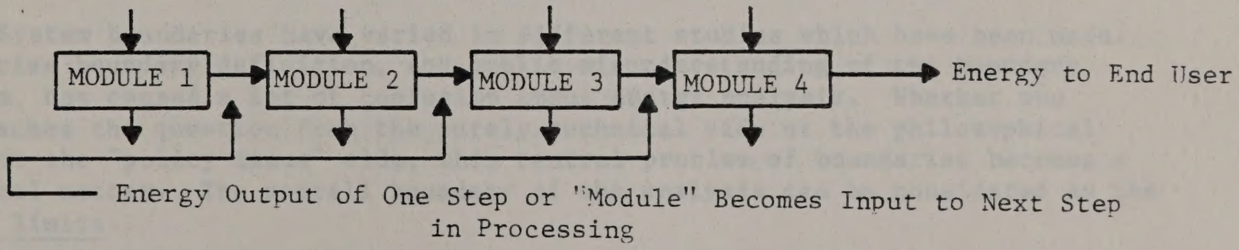

MODULE 1
MODULE 2
MODULE 3
MODULE 4
Energy to End User
Energy Output of One Step or "Module" Becomes Input to Next Step in Processing

FIGURE 2.1c
Module String or "Trajectory"

FIGURE 2.1
Energy Production "Modules": Concept

Product." The heat which goes up the chimney is a loss, shown here as a downward arrow from the module. The electricity required is an input of "External Energy". Since it can do no further work after it is used in the furnace motor, it is then "lost" and is part of the downward energy flow from the module.

The electricity was produced from some other energy source and conversion system, such as a hydroelectric or coal-fired generating plant. The water power or coal is as essential to the system operation as the natural gas, but must be viewed as "indirect" energy requirements or inputs. The same applies to the materials of the furnace and fan, and to the energy required to produce those materials and construct a furnace and fan from them.

Figure 2.1b shows the concept of these indirect energy inputs.

Hence, it can be seen that an operational furnace requires a variety of inputs. This specific example is for an energy-conversion system at the point of end use of energy. This handbook deals with energy production systems, not end-using devices, but the principle of inputs and outputs of a simple system is the same. Energy production systems usually contain a number of operations in extracting, converting and moving energy. They are much more complex than the simple example of the furnace; i.e., their boundaries are much broader. Figure 2.1c displays the concept of a series of operations or modules in a larger system of producing and transporting energy, with the flow of energy being processed shown as a left-to-right horizontal flow, and the output of one operation becoming the input to the next operation to the right.

However, it is recognized that many other relationships exist between the direct system of energy production, its direct and indirect inputs, the resources which go into the system, and the social, economic and biophysical environments which interact with these other elements of the system. Hence, the boundaries of the system could be considered to encompass a good many elements.

The energy analyst must determine boundaries which allow him to eliminate the unimportant, the elements which are numerically or philosophically irrelevant to his study, and to deal only with a manageable system.

2.1.2 System Boundary Considerations

System boundaries have varied in different studies which have been made. Imprecise boundary definition, and public misunderstanding of the boundary issues, has caused a lot of confusion about energy analysis. Whether one approaches the question from the purely technical side or the philosophical side or the "policy issue" side, this central problem of boundaries becomes a critical matter. The overall boundary of the analysis can be considered as the study limits.

Boundary identification must deal first with the comprehensiveness of the system, and second with some specific inclusions and exclusions if a less-than-comprehensive system is defined. The concept of "net energy analysis" does not preclude the examination of very large systems including a variety of types of energy flows.

The entire concept of the study limits and boundaries will be considered in the context of modules, energy systems, and inputs and outpus which has just been discussed. Terminology will be introduced which will be utilized throughout the rest of the handbook. The discussion of boundaries will commence with a more detailed treatment of modules, trajectories, and inputs and outputs.

In the terminology of this handbook, the entire flow of energy being processed, from left to right through the various operations, is called a "trajectory."

A single module, or major operation in a trajectory, has inputs and outputs as previously discussed, and repeated in greater detail in Figure 2.2. This shows that it takes materials to make energy to make materials, etc. The inputs to the module are called:

Principal Energy -- Energy to be processed or transported.

External Energy -- Energy required from outside to operate the process and to make the materials needed to build and operate the processing system.

The outputs are:

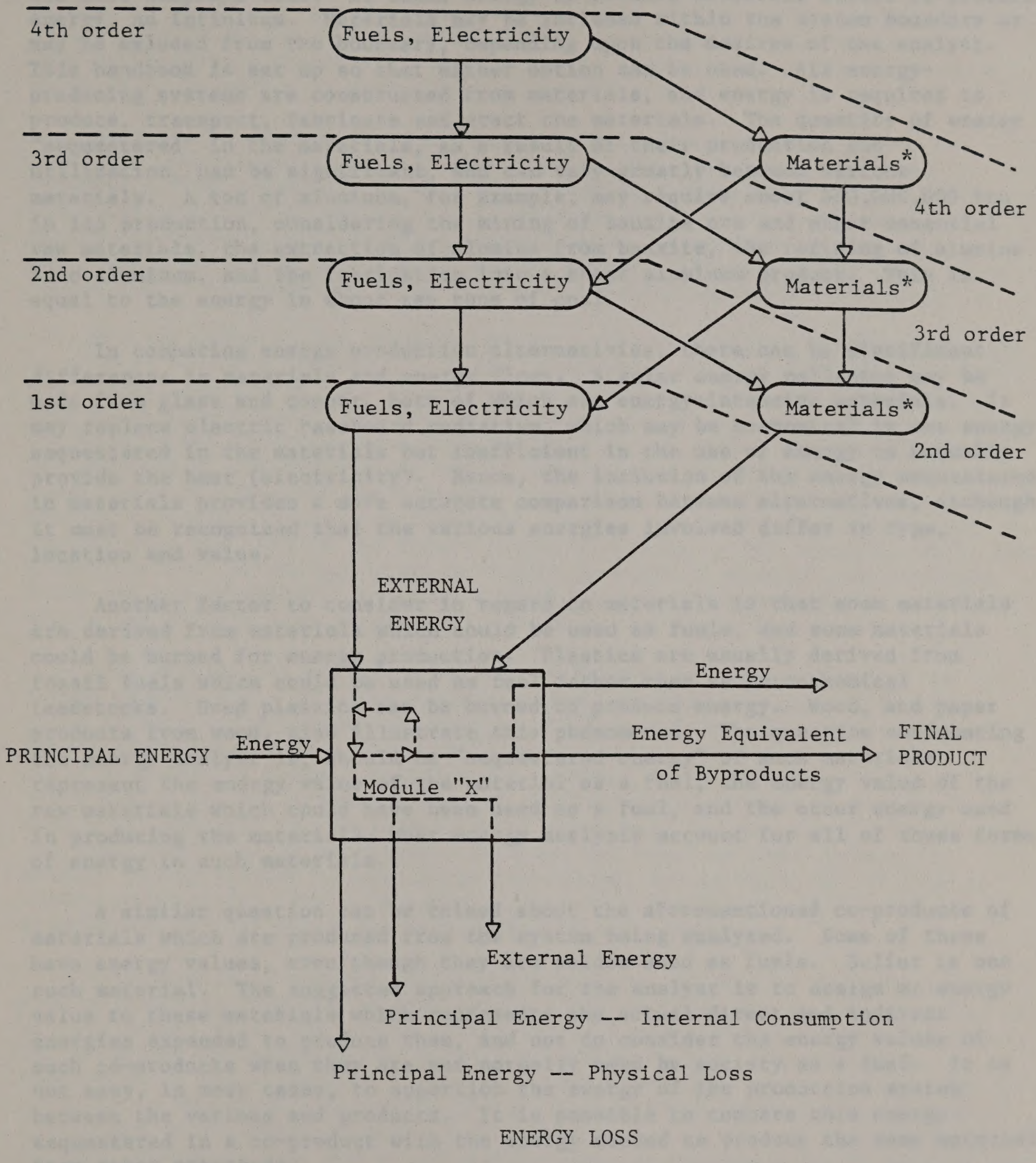
Energy Product -- Processed or transported energy delivered from the process.

Energy Loss -- Energy unavailable for further use as a result of the process; this can include physical losses, unrecovered resources in extraction, internally consumed energy, and external energy.

The losses are somewhat different for each module and will change as technology improves in the future. This study will assume technologies that may be on line by the late 1980's and will also assume that economics will not radically change so that inputs and outputs of any module will change significantly in the future.

The final output is identified by energy type (gas, gasoline, coal, electricity) as a general indicator of the quality of the energy. "Quality," as defined herein, refers not only to thermodynamic properties of different forms of energy but also to social-value factors such as location, transportability, storability, utility, etc. Energy qualities are as important as energy quantities. Quality changes as energy is processed, and external energy inputs are comprised of different qualities of energy. Hence, a trajectory represents quantitative measurements (British thermal units, for instance) but is qualitatively a mix of different types of energy. Further discussion of energy quality is found in this chapter.

The energy product can include one or more types of energy and can also include materials as shown in Figure 2.2. At least two oil shale operations have been proposed which will produce shale oil, nahcolite, soda ash and possibly alumina. The upgrading of the shale oil may produce sulfur and ammonia as saleable by-products. This situation leads to the problem of assigning an energy value to the co-products of both energy and materials.



*Materials include raw materials, containers, machinery, consumable manufactured items (catalysts, lubricants, chemicals, process additives, etc.), tools, pipelines, wiring, construction materials, and road materials (asphalt, cement, tar, steel, etc.).

FIGURE 2.2
Energy Flows Generalized Module "X"

The inputs to the energy production system also include materials. Figure 2.2 also displays this: it takes energy to produce materials needed to produce energy, ad infinitum. Materials may be included within the system boundary or may be exluded from the boundary, depending upon the desires of the analyst. This handbook is set up so that either option can be used. All energy-producing systems are constructed from materials, and energy is required to produce, transport, fabricate and erect the materials. The quantity of energy "sequestered" in the materials, as a result of their production and utilization, can be significant, and can vary greatly between various materials. A ton of aluminum, for example, may require about 250,000,000 Btu in its production, considering the mining of bauxite ore and other essential raw materials, the extraction of alumina from bauxite, the refining of alumina into aluminum, and the fabrication into a sheet aluminum product. This is equal to the energy in about ten tons of coal.

In comparing energy production alternativies, there can be significant differences in materials and energy flows. A solar energy collector may be made from glass and copper, both of which are energy-intensive materials. It may replace electric baseboard radiation, which may be economical in the energy sequestered in the materials but inefficient in the use of energy to actually provide the heat (electricity). Hence, the inclusion of the energy sequestered in materials provides a more accurate comparison between alternatives, although it must be recognized that the various energies involved differ in type, location and value.

Another factor to consider in regard to materials is that some materials are derived from materials which could be used as fuels, and some materials could be burned for energy production. Plastics are usually derived from fossil fuels which could be used as fuel rather than as petrochemical feedstocks. Used plastics can be burned to produce energy. Wood, and paper products from wood, also illustrate this phenomenon. The question confronting the energy analyst is, should be "sequestered energy" of such materials represent the energy value of the material as a fuel, the energy value of the raw materials which could have been used as a fuel, and the other energy used in producing the material? Most energy analysts account for all of these forms of energy in such materials.

A similar question can be raised about the aforementioned co-products of materials which are produced from the system being analyzed. Some of these have energy values, even though they are seldom used as fuels. Sulfur is one such material. The suggested approach for the analyst is to assign an energy value to these materials which represents the actual direct and indirect energies expended to produce them, and not to consider the energy values of such co-products when they are not normally used by society as a fuel. It is not easy, in most cases, to apportion the energy of the production system between the various end products. It is possible to compare this energy sequestered in a co-product with the energy needed to produce the same material from other processes.

The methodologies for analyzing "sequestered energy" in materials will be discussed in greater detail later in the handbook.

A number of special-purpose "net energy" studies have dealt with a single and specific process such as an oil-shale plant in isolation. The boundary

begins and ends immediately at the fence of the module. This leads to a study of limited value. It may be useful in a process analysis of a specific process to identify potential energy inefficiencies or direct and indirect inputs. This may assist in pinpointing some potential energy input problems or costs which could be masked by pure economic analysis.

However, it ignores the fact that a single process does not stand by itself in the "assembly line" of energy production. To bring a mineral resource to the end users, it must be extracted, processed to produce different qualities and forms of energy, and moved about quite a bit to get it to the various processers, distributors, and end users. Each step requires energy. Also, since one resource may move through several different trajectories, any comparison of alternatives or options must consider the entire trajectory.

The inclusion of the resource which is effectively lost due to production is another boundary problem. Does the unrecovered or lost resource lie within the system boundary or not? A case can be made for either point, depending upon which issues one is addressing. However, it is diligently incumbent upon the analyst who includes gross resources within his system boundary to advise his audience of his assumptions and of some hazards which he has created in comparisons of different trajectories. An "unrecovered resource" assumes that present technologies and economics will previal. Changes in economics and technologies may lead to the future recovery of some of the resources which are unrecoverable. An example might be future recovery of some of the resources which are unrecoverable. An example might be future in-situ recovery of shale oil in the pillars left in place in oil shale room-and-pillar mining.

The resource not extracted may not be damaged or permanently lost to future generations. In petroleum extraction, that amount left in the ground after primary and secondary recovery is still petroleum. The U.S. Geological Survey identifies it as a "resource", but it is not a "reserve" according to the U.S. Bureau of Mines classification system. See Figure 2.3. It is subeconomic, but it is there. Even if tertiary recovery were to become economical and lead to the production of about half the petroleum of the field, the remainder is still petroleum. It might be "lost" to this generation because of our present economics and technology, but it might not be lost to future generations. The only petroleum which is permanently lost to future generations is that which has been extracted and consumed.

Human energy is another factor which must be included or excluded from the system boundary. Similar considerations apply in this case as in the matter of natural ecosystems. The energy assignable to a given energy alternative should be the metabolic energy of the workers allocated to that alternative in proportion to the difference in its net energy from that of the alternative to which it is compared. (Metabolic energy is that which is used directly and internally by the human organism.) In other words, if Process A needs 50 workers' energy output, and a less labor-intensive Process B has 40 workers for the same output, then the human energy assigned could be that of 10 workers. The metabolic energy, rather than "life style" energy, should be assigned. The "life style" energy of an individual should not be assigned entirely to his job. Life style energy includes the entire urban infrastructure and services consumption of energy. As with ecosystem energy, the human energy will be insignificant compared to industrial energy. One study states that the inputs

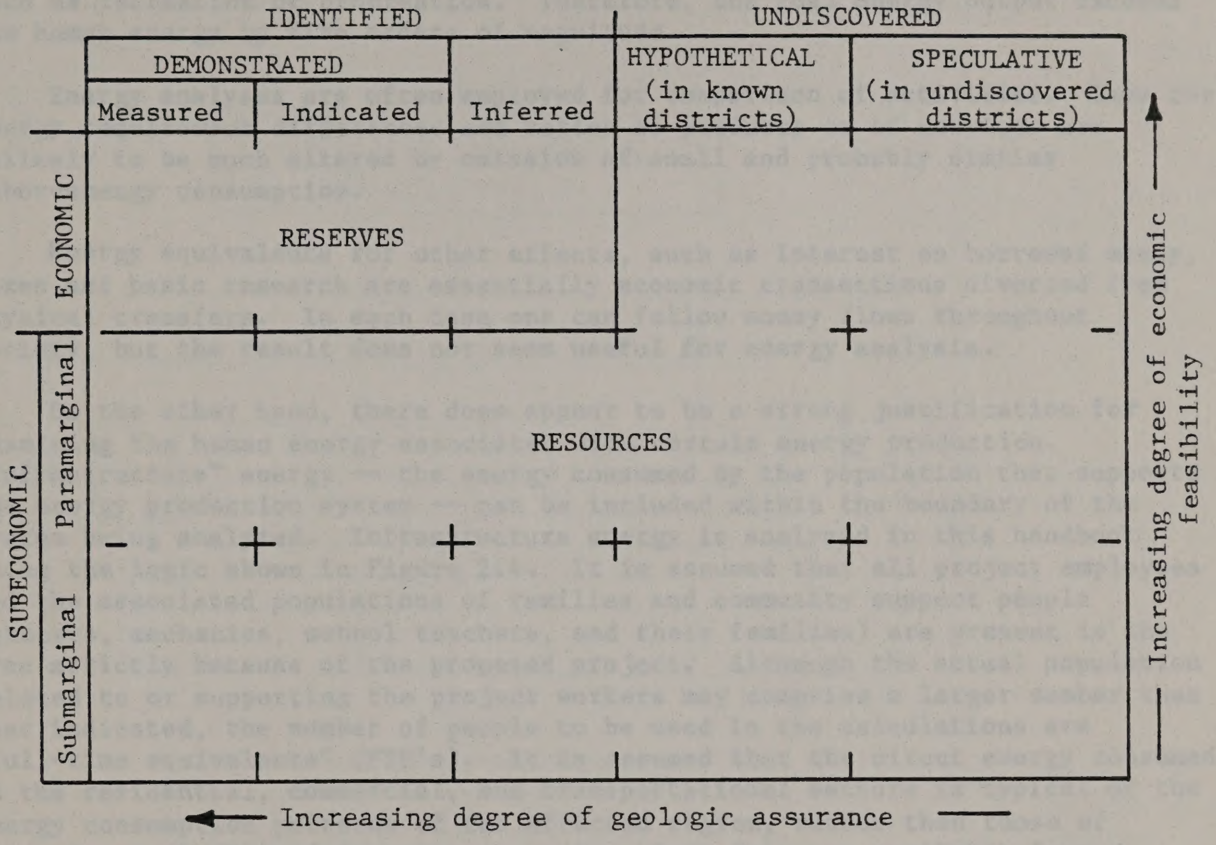

IDENTIFIED
UNDISCOVERED
DEMONSTRATED
Measured
Indicated
Inferred
HYPOTHETICAL (in known districts)
SPECULATIVE (in undiscovered districts)
ECONOMIC
RESERVES
SUBECONOMIC
Paramarginal
Submarginal
RESOURCES
Increasing degree of economic feasibility
Increasing degree of geologic assurance

FIGURE 2.3
Resource Classification Diagram by the U. S. Geological Survey and the U. S. Bureau of Mines

to an ammonia process may be 40,000 Gigajoules (GJ) per day compared to the worker household energy use of 0.22 GJ/day (80 GJ/year) per worker; for 200 workers, this is 44 GJ/day.

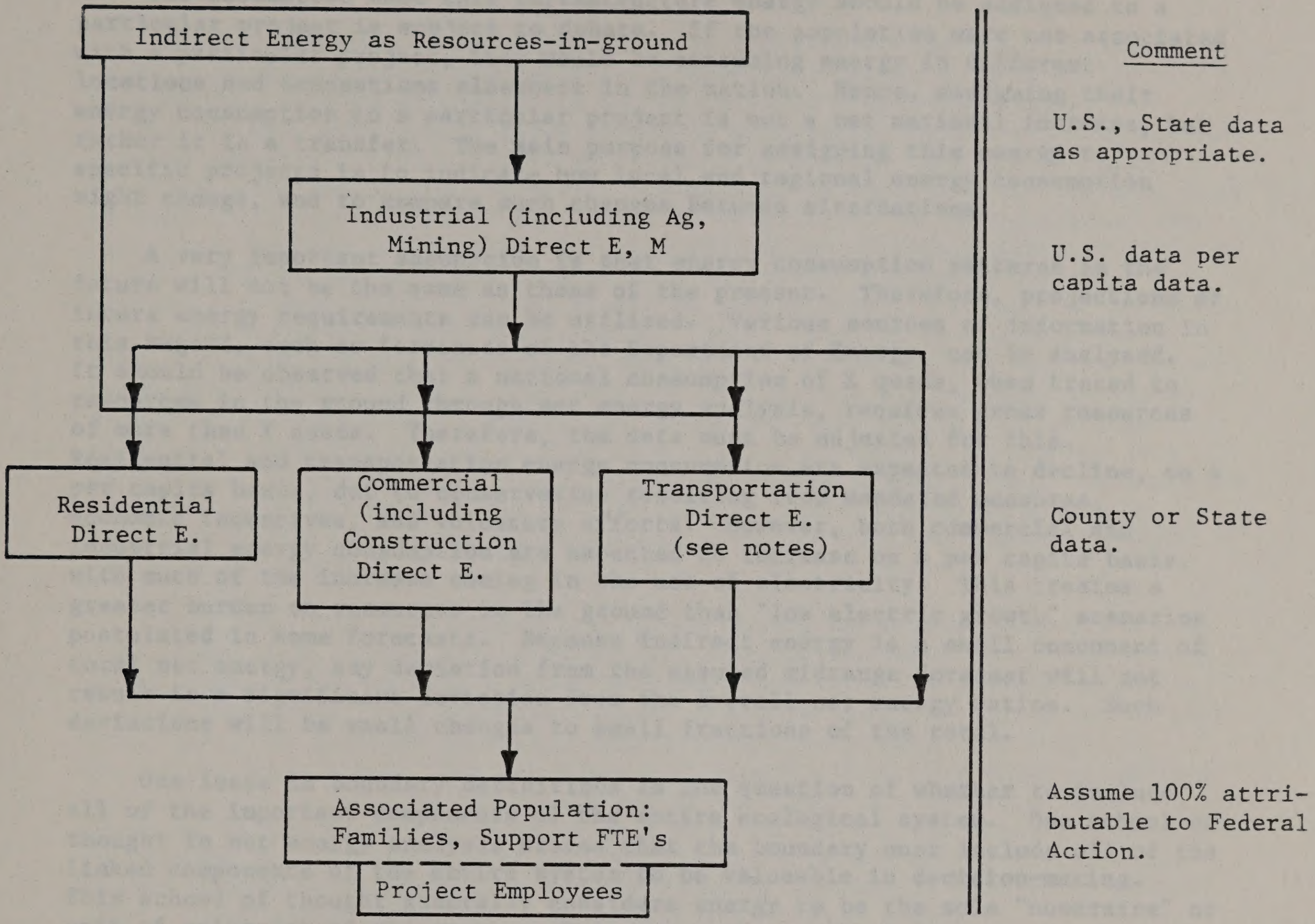
For a strip mine with 50 men producing 1 million tons/year, or say 2.2 x 10^{13} Btu/year, the metabolic energy would be 50 men times 12,000 Btu/day x 365 days/year = 2.2 x 10^{8} Btu/year. This assumes 100 percent of the human energy assigned to mining and none to any other aspects of the workers' lives, such as recreation or procreation. Therefore, the coal energy output exceeds the human energy by five orders of magnitude.

Energy analyses are often employed for comparison of activities. Thus the energy requirement differences and ratios of products or of services are unlikely to be much altered by omission of small and probably similar labor-energy consumption.

Energy equivalents for other effects, such as interest on borrowed money, taxes and basic research are essentially economic transactions divorced from physical transfers. In each case one can follow money flows throughout society, but the result does not seem useful for energy analysis.

On the other hand, there does appear to be a strong justification for examining the human energy associated with certain energy production. "Infrastructure" energy -- the energy consumed by the population that supports the energy production system -- can be included within the boundary of the system being analyzed. Infrastructure energy is analyzed in this handbook using the logic shown in Figure 2.4. It is assumed that all project employees and the associated populations of families and community support people (grocers, mechanics, school teachers, and their families) are present in the area strictly because of the proposed project. Although the actual population related to or supporting the project workers may comprise a larger number than that indicated, the number of people to be used in the calculations are "full-time equivalents" (FTE's). It is assumed that the direct energy consumed in the residential, commercial, and transportational sectors is typical of the energy consumption patterns of the affected region, rather than those of Colorado or the United States as a whole. Such data are available from a recent study for Colorado. However, direct energy used by the industrial sector and associated with the project FTE's is not that of the affected region. The project-related population will drive cars made in Detroit made from steel produced in Indiana from iron ore mined in Minnesota; they will wear clothes with fabrics originating in Texas petrochemical plants, etc.

The industrial sector energy consumption is not consumed directly by the FTE population but is in effect "embodied" in the material objects used by or supporting this population. Energy is needed to produce cement, copper, and glass in the residences and steel and other materials in commercial buildings and furnishings, in vehicles, and so forth. This energy cannot be ignored, as it is a major component of the energy requirements of each person in an industrial society. Conversely, industrial products produced in the region may not be utilized by the regional population but may be exported from the region and used nationally. Therefore, the industrial sector energy consumption should be considered on a national basis. Indirect energy, traced to resources in the ground, can be calculated in a manner similar to that discussed for the


Indirect Energy as Resources-in-ground
Comment
U.S., State data as appropriate.
Industrial (including Ag, Mining) Direct E, M
U.S. data per capita data.
Residential Direct E.
Commercial (including Construction Direct E.
Transportation Direct E. (see notes)
County or State data.
Associated Population: Families, Support FTE's
Project Employees
Assume 100% attributable to Federal Action.

(1) E = Energy
(2) Industrial energy is sequestered in materials M utilized by all sectors and associated population's "final demand" of goods and services.

FIGURE 2.4
Infrastructure Energy: Concept

basic trajectory energy consumption. As with direct energy, indirect energy will, assumedly, have regional characteristics for residential, commercial, and transportation energy consumption and national characteristics for the industrial sector energy.

The assumption that this infrastructure energy should be assigned to a particular project is subject to debate. If the population were not associated with a particular project, they would be consuming energy in different locations and occupations elsewhere in the nation. Hence, assigning their energy consumption to a particular project is not a net national increase, but rather it is a transfer. The main purpose for assigning this energy to specific projects is to indicate how local and regional energy consumption might change, and to compare such changes between alternatives.

A very important assumption is that energy consumption patterns in the future will not be the same as those of the present. Therefore, projections of future energy requirements can be utilized. Various sources of information in this regard, such as forecasts of the Department of Energy, can be analyzed. It should be observed that a national consumption of X quads, when traced to resources in the ground through net energy analysis, requires gross resources of more than X quads. Therefore, the data must be adjusted for this. Residential and transportation energy consumption are expected to decline, on a per capita basis, dut to conservation resulting from mandated measures, economic incentives, and voluntary efforts. However, both commercial and industrial energy consumption are expected to increase on a per capita basis, with much of the increase coming in the use of electricity. This creates a greater burden on resources in the ground than "low electric growth" scenarios postulated in some forecasts. Because indirect energy is a small component of total net energy, any deviation from the assumed midrange forecast will not result in a significant deviation from the overall net energy ratios. Such deviations will be small changes to small fractions of the total.

One issue in boundary definitions is the question of whether to include all of the important components of the entire ecological system. One school of thought in net energy analysis states that the boundary must include all of the linked components of the entire system to be valueable in decision-making. This school of thought generally considers energy to be the sole "numeraire" or unit of valuation of the system. This approach is called "energy theory of value." Within the urban-industrial component of the system, for instance, money would be replaced by energy as the numeraire for transactions. The premise is that the only common flow within and between all components of the universe is energy. Money flows and energy flows would be related, but energy would primarily describe the system behavior.

There are a number of reasons for excluding ecosystem energy flows from a generalized study of industrial energy production. First, energy flows in ecosystems may be numerically insignificant. For example, consider the 10-year loss of primary production of an irrigated alfalfa field if it is disturbed to recover a 15-foot seam of coal and then restored to alfalfa production. This loss is, in a sense, a social subsidy of the fossil fuel system. However, the fossil fuel system also "subsidizes" the agriculture system. The energy from the coal is about 100,000 times that lost in the 10-year disturbance of the

alfalfa. This quantity will be lost in the numerical "noise" or deviations in the industrial system numbers. (Decision-making based on energy values alone would always lead to the loss of the alfalfa field, thus ignoring the need for the energy qualities of alfalfa and the other values associated with the alfalfa field.)

Second, ecosystem energy disruption is highly site-specific. Primary production varies from 0.5 x 10^3 Kcal/m^2/year in a desert to 20 x 10^3 Kcal/m2/year in some estuaries and wet broadleaved evergreen forests. Changes in ecosystem energy flows should be analyzed in site-by-site ecological studies associated with specific development proposals. The energy flows should be analyzed in the context of the ecological analysis, and concepts such as beneficial use of "waste" heat could be considered. Detailed process and ecological studies of the site and a specific proposed energy industry would be needed. Third, distance and time factors are highly variable, and are difficult to deal with. Fourth, ecosystem energy disruptions may be the result of cumulative effects from many sources. Also, they can be assessed for different conditions: for existing conditions, for conditions under ecosystem management for increased productivity, or for natural successional or climax stages of the ecosystem. Lastly, the energy produced from a mine or power plant will vary greatly per unit of land surface affected. Coal seams vary significantly, for example. Thus, site specificity becomes highly important to any meaningful analysis. This problem becomes infinitely complex when an entire trajectory of energy production is examined from the mineral resource to the point of end use.

Time, the fourth dimension, can be considered as another boundary. The many flows in an energy system do not all occur at the same time. The energy which produced the materials which have gone into specific power plants that process energy may have occurred decades ago. The energy output from the power plant which is recycled back into future energy production will involve additional time flows. One can display a "static" condition which recognizes and accounts for various time flows and boundaries. One the other hand, there are ways in net energy analysis to deal explicitly with the time dimension and to display it. The essence of the point is that in net energy analysis the fourth dimension boundary is a very real matter and can be handled in several ways. Some issues cannot be handled only with static analysis.

By-product outputs may be included or excluded from the boundary and the accounting of energy. Some processes may be intended to put out only one product; others may be deliberately designed to produce various energy products. For example, a power plant could supply heat from its boilers to a number of buildings for house heat and hot water heating. This "waste heat" would be a valuable by-product in this case. It would be feasible to use it because of the proximity of the plant to potential end users of heat and lower quality.

If all energy by-products, or materials by-products which represent the sequestering of energy in their manufacture, are not included in the analytical boundary and accounting, then the energy inputs proportional to their share of the total output should be excluded. The data and accounting problems which apply to net energy analysis in general are also applicable to by-products.

Some energy-producing systems require combustion air, cooling air and water, water for hydrogenation and other purposes. Inasmuch as they have no enthalpy of combustion, it is realistic to exclude them from the calculations. However, it is proper to include the energy required to move them so that the production process can operate.

One more boundary inclusion or exclusion matter which has been controversial is research energy. Energy research per se is not directly intended to produce energy. It is usually intended to lead to an energy production improvement or a new process; these latter are then intended to produce energy. Much research is dead-end; that is the nature of research. Also, research results are transferred. For instance, Rankine cycle engines were not thought up for "bottoming cycle" use in solar thermal-electric plants, but they may be so used. The fluidized bed was invented for making coke, but is used in many other processes such as refineries (fluid-bed catalytic cracking). How much of the fluidized bed research energy should be assigned to coke and how much to other processes? Further, if such an assignment were made, the amount of energy would probably be negligible compared with other energy inputs and outputs. Also, if research energy is to be allocated to some ultimate production, then one must have some idea of what the ultimate quantity of that future production will be. For these reasons, it seems proper to exclude research energy costs.

In a number of operations in energy production, some the product may be used internally within the general operation, thereby reducing the need to procure energy from outside of the module. This energy can either be part of the energy product, bled off before it crosses the output boundary of the plant, or it can be recovered from "waste" energy. An example of the first condition would be petroleum refinery, in which oil being processed is bled off to fire steam boilers needed for heating the feed into a distillation tower. An example of the second condition would be an economizer in a fossil fuel-fired steam boiler; boiler feed water is preheated by "waste" heat in the stack gases. If this preheating were not done in the economizer, either external energy would have to be procured to preheat boiler feed water or the boiler feed water could be introduced cold into the boiler, thereby reducing efficiency and net energy yield of the boiler.

Figure 2.5 shows the concept of recycled energy for a single module. Note that the inputs of Principal Energy and External Energy must always equal the outputs of Energy Product and Losses (See Figure 2.2). The first process, Figure 2.5a, is driven with external energy. The second, Figure 2.5b is operated on internal energy. It never appears outside the boundary and therefore is not accounted for. This makes the net energy yields look very favorable because it reduces the external energy which is acquired to drive the process. Figure 2.5c, in effect, takes this same internal driving energy outside the boundary and then returns it as a net energy deduction. This is a problem of accounting methods as well as boundaries. In all the cases of Figure 2.5, the same amount of energy is needed to operate the system. Figure 2.5c merely disguises the driving energy by hiding it inside the boundary; also, if one wants a "balance", this energy must be shown as the loss shown in Figure 2.5c. The accounting method described in the methodology avoids this particular pitfall of boundaries.

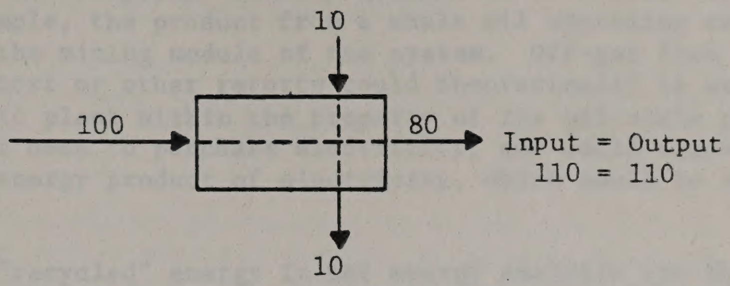


FIGURE 2.5a

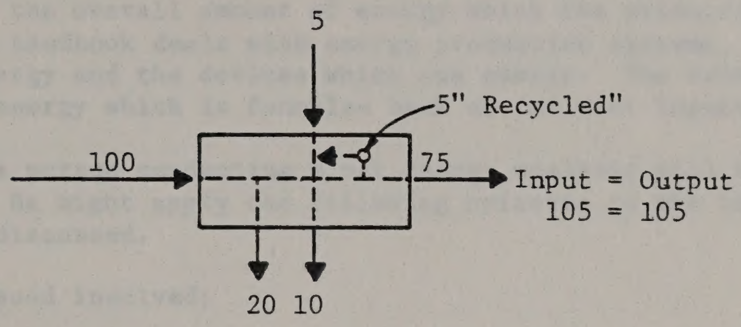


FIGURE 2.5b

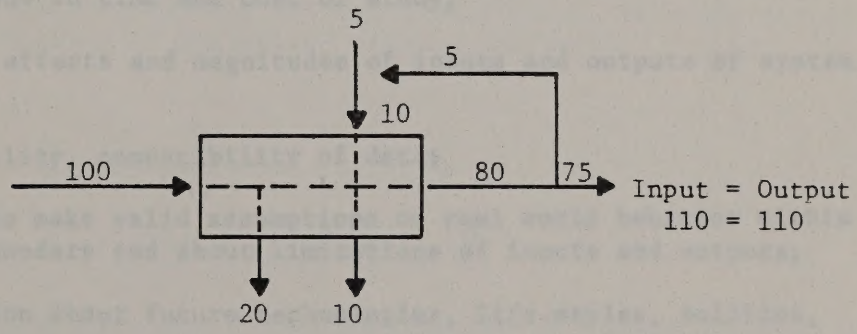


FIGURE 2.5c

FIGURE 2.5
Internal and External Energies:
Boundary Options for Module

Energy can also be "recycled" between modules of an overall system or trajectory. For example, the product from a shale oil upgrading unit could be used as fuel oil in the mining module of the system. Off-gas from a modified in situ oil shale retort or other retorts could theoretically be used as fuel for a thermal-electric plant within the property of the oil shale producer. This would reduce the need to purchase electricity, and could conceivably lead to production of an energy product of electricity, which could be sold to the public.

The problem of "recycled" energy in net energy analysis can be dealt with in various ways. Subsequent chapters will expound the methods to be used in this handbook.

A final important portion of the system which must be considered is the end use of energy. End use devices and uses, which are affected by users' lifestyles, dictate the overall amount of energy which the production system must deliver. This handbook deals with energy production systems, not with final demand for energy and the devices which use energy. The exception is the portion of end-use energy which is funneled back as indirect inputs.

In summary, the person conducting a net energy analysis will have to select a boundary. He might apply the following criteria to the boundary options previously discussed.

- Social issued involved;
- Desired level of specificity;
- Potential use in decision-making;
- Limitations in time and cost of study;
- Decay of effects and magnitudes of inputs and outputs of system selected;
- Comparability, compatibility of data;
- Ability to make valid assumptions on real world behavior within system boundary and about limitations of inputs and outputs;
- Speculation about future technologies, life styles, politics, economics;
- Realism of time frames in tems of technological and other dynamics (the "fourth dimension" boundary);
- Site-specificity of concerns and proposals to be analyzed.

For the purposes of the Bureau of Land Management, the boundaries selected are shown in general in Figure 2.6. However, different energy accounting systems can modify the boundaries as regards indirect energy and resources in the ground. This will be discussed later in this chapter.

2.1.3 Three Energy Issues and Accounting Methods

There are three basic issues of "net energy." Different data are used for quantifying each issue. Each issue has an appropriate accounting method, and each issue relates to a different "boundary" within the overall boundary of the study.

For each issue, an appropriate accounting method can quantify results as both a total of input and outputs and a ratio of outputs to inputs. Ratios are a standard mathematical approach for expressing one quantity (output) relative to another (input). However, ratios must be used cautiously; for example, a small change in the denominator causes a large change in a ratio. In net energy analysis, the use of internally recycled process energy for plant operations, instead of the use of external energy, can significantly affect Ratio R-1 (described below).

These issues and accounting methods are as follows, referring to the following Figures 2.7 through 2.9, for terminology.

(a) Issue: How much energy is required from the industrial component of society to "drive," or establish and operate an energy production process, relative to the energy yield of the process. See Figure 2.7.

Accounting Methods:

(1) Net Yield

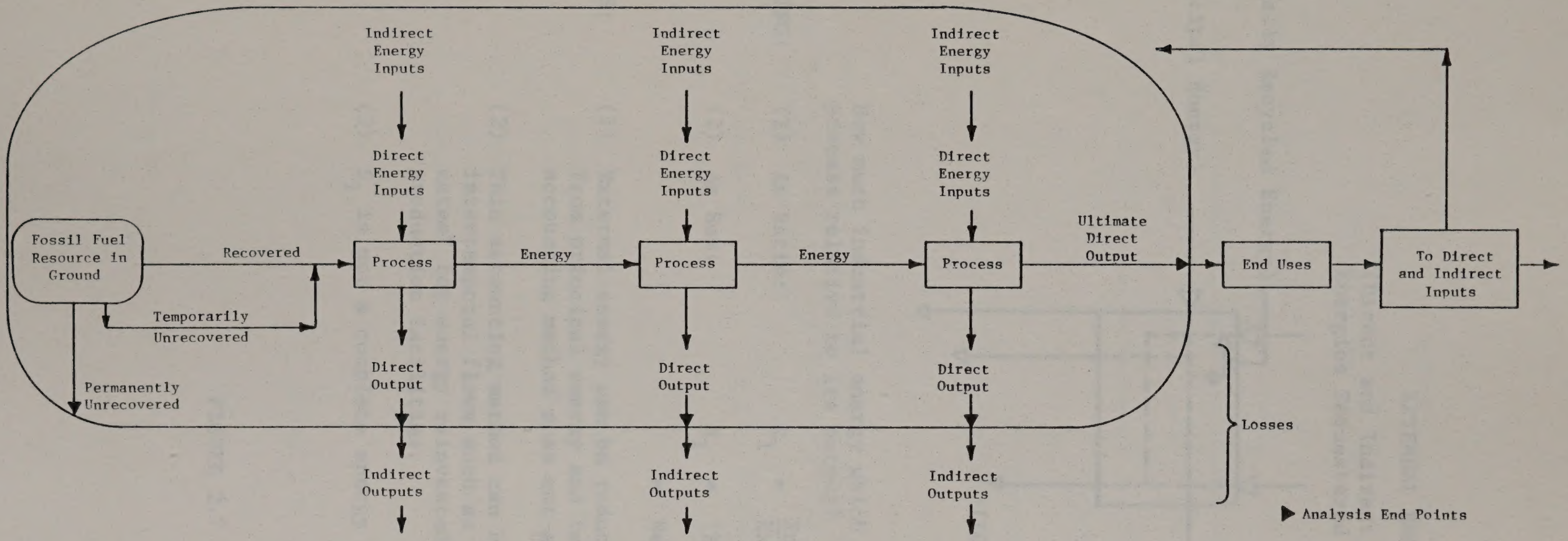
By subtracting the external energy from the final output, the yield is shown. This is not a true balance for a module. For comparative purposes between trajectories, external energy can be compared if trajectory outputs are equal.

(2) Ratio

Ratio R_1: External Net Energy Ratio"

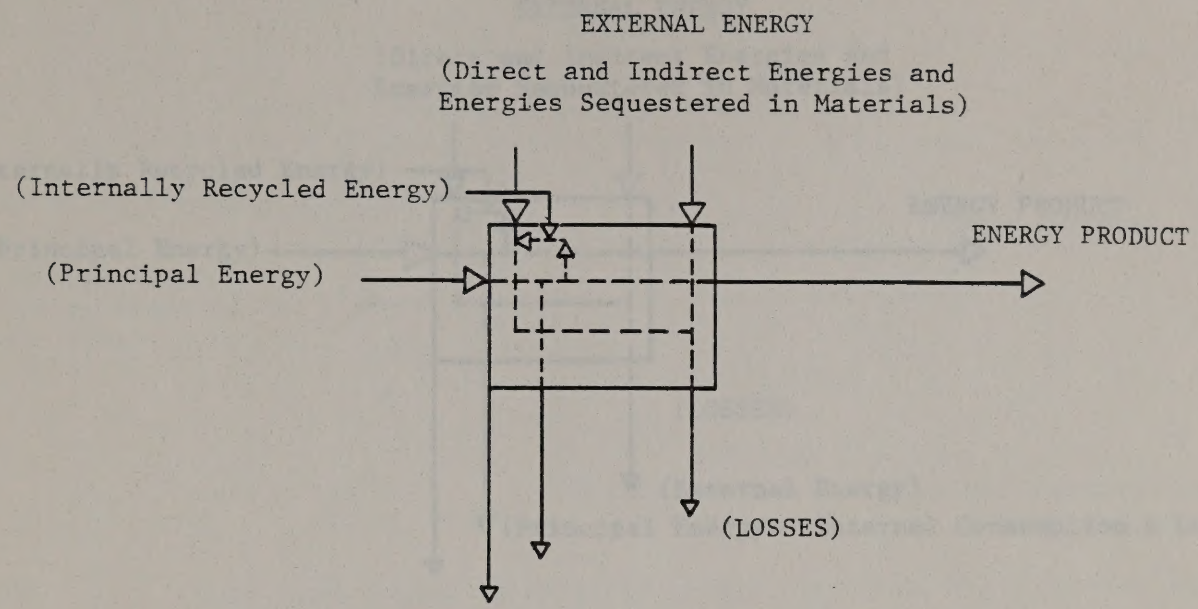
$$\text{Ratio:} = \frac{\text{Total ENERGY PRODUCT out}}{\text{Total EXTERNAL ENERGY in}}$$

(b) Issue: In extracting, processing, and moving fossil fuels to provide energy to end users, what are the final yields relative to losses of the total energy of the recovered fossil fuel resource and of the industrial energy needed to establish and operate the fossil energy production systems? See Figure 2.8.



	Indirect Inputs	Direct Inputs	Direct Outputs	Indirect Outputs
In Study Boundary	Energy Materials	Energy Materials Water	Energy, Heat Materials Usable Byproducts Unusable Salvage	
Optionally in or Outside Study Boundary	Urban System Infrastructure of Services, Transportation, Housing, Commerce, Social System, etc.		Water	
Outside Study Boundary	Intellect Ecosystems Food Systems Financial Government Systems Hydrological Systems	Labor Intellect Finances Land	Finances	Ecosystem Disruption Health Social Systems Economic Systems Land Use Food Systems

FIGURE 2.6
Net Energy Analysis System Elements


EXTERNAL ENERGY
(Direct and Indirect Energies and Energies Sequestered in Materials)
(Internally Recycled Energy)
(Principal Energy)
ENERGY PRODUCT
(LOSSES)

ISSUE: How much industrial energy which must be invested in a process relative to its output?

ACCOUNTING: (1) As Ratio: $R_1 = \dfrac{\text{Energy Product}}{\text{External Energy}}$

(2) As Sum: $S_1 = (\text{Energy Product}) - (\text{External Energy})$

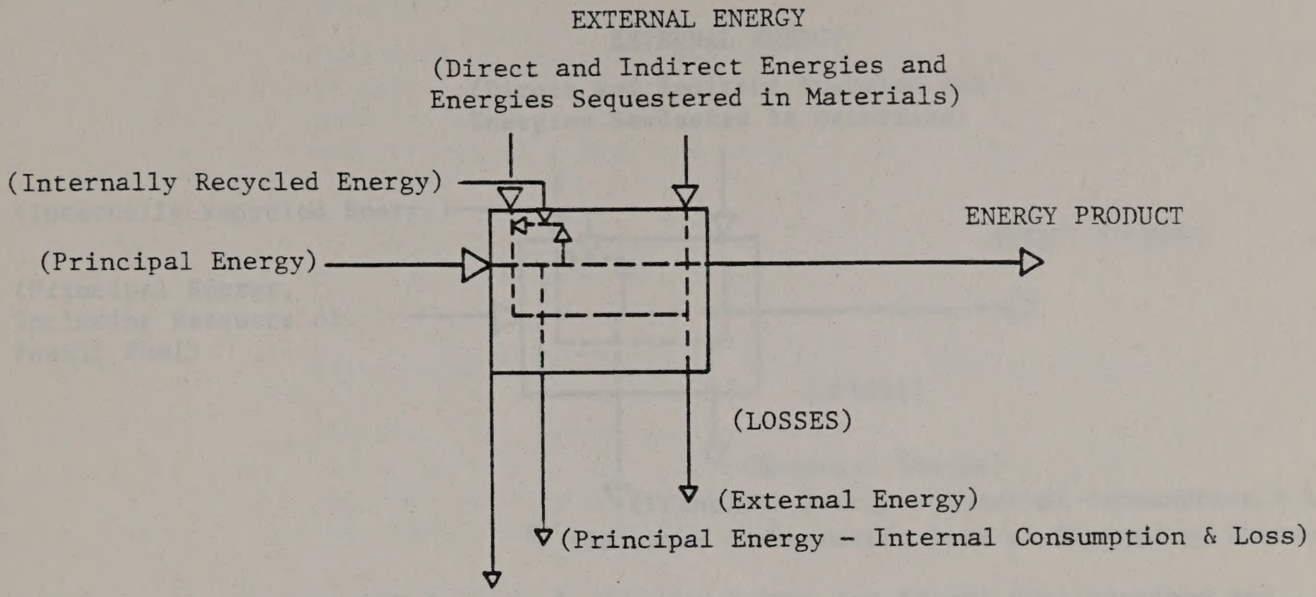
$= \text{Net Yield}$

COMMENTS: (1) External energy can be reduced by recycling energy which comes from principal energy and is produced by the process; this accounting method does not show this situation.

(2) This accounting method can be used in further analysis of intertemporal flows such as "payback periods" or "reinvestment rates" for energy reinvested to achieve new growth in energy production facilities.

(3) S_1 is not a complete energy balance.

FIGURE 2.7


EXTERNAL ENERGY
(Direct and Indirect Energies and Energies Sequestered in Materials)
(Internally Recycled Energy)
ENERGY PRODUCT
(Principal Energy)
(LOSSES)
(External Energy)
(Principal Energy - Internal Consumption & Loss)

ISSUE: What final yields of energy product do we get relative to the total social losses of recovered resources and industrial energies from outside the process?

ACCOUNTING: (1) As Ratio: $R_2 = \frac{\text{Energy Product}}{\text{Losses}}$

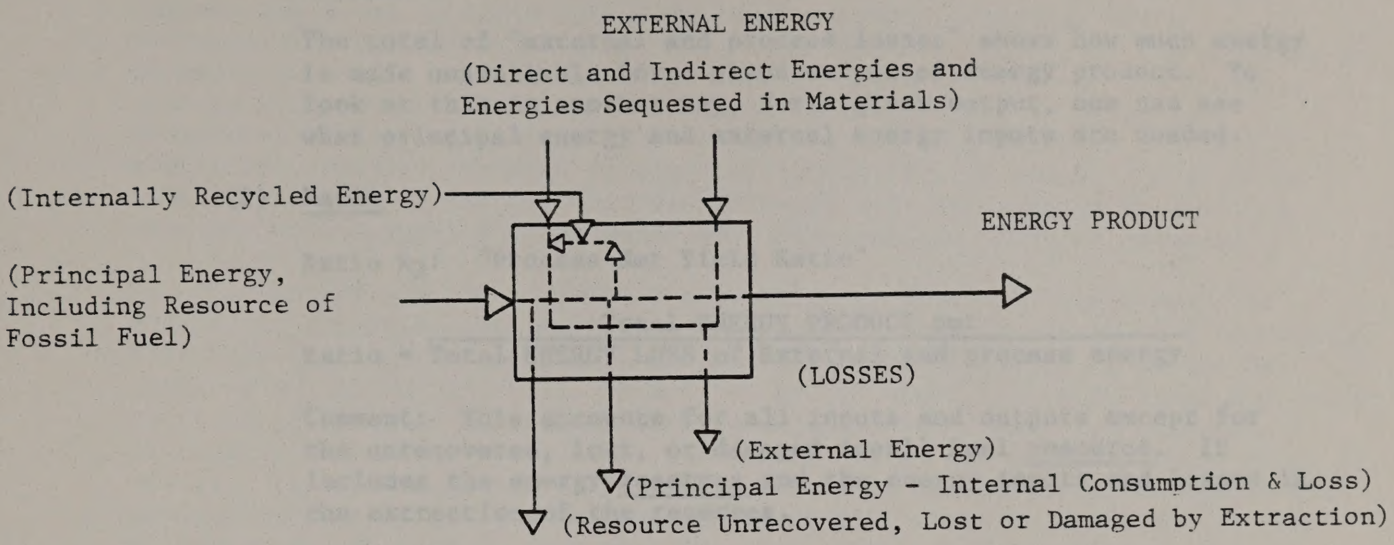
(2) As Sum: $S_2 = \text{(Principal Energy)} - \text{(Losses)}$

$= \text{Net Yield}$

COMMENTS: (1) Variation between external energy and recycled internally-generated energy does not affect the accounting, as both of these energies end up as losses.

(2) This addresses impacts on reserves of fossil fuels, and could be used in intertemporal analysis which examines depletion rates.

FIGURE 2.8


EXTERNAL ENERGY
(Direct and Indirect Energies and Energies Sequested in Materials)
(Internally Recycled Energy)
ENERGY PRODUCT
(Principal Energy, Including Resource of Fossil Fuel)
(LOSSES)
(External Energy)
(Principal Energy - Internal Consumption & Loss)
(Resource Unrecovered, Lost or Damaged by Extraction)

ISSUE: What total losses of external energy and fossil fuel reserves and resources occur to achieve a certain output of energy product?

ACCOUNTING: (1) As Ratio: $R_3 = \frac{\text{Energy Product}}{\text{Losses}}$

(2) As Sum: $S_3 = \text{(Principal Energy)} - \text{(Losses)}$

$= \text{Net Yield}$

COMMENTS: (1) This gives a more accurate picture of resource stress than Method 2, as it displays the resource which is no longer available to society, given today's economics and technology, once the process is in operation.

(2) Comments (1) and (2) from METHOD 2 apply.

FIGURE 2.9

Accounting Methods:

(1) Net Yield

The total of "external and process losses" shows how much energy is made unavailable for a given output of energy product. To look at this in another way, for a given output, one can see what principal energy and external energy inputs are needed.

(2) Ratio

Ratio R_2: "Process Net Yield Ratio"

$$\text{Ratio} = \frac{\text{Total ENERGY PRODUCT out}}{\text{Total ENERGY LOSS of External and process energy}}$$

Comment: This accounts for all inputs and outputs except for the unrecovered, lost, or damaged fossil fuel resource. It includes the energy reserves and the energy inputs and losses in the extraction of the reserves.

(c) Issue: For a given output of fossil fuel energy for end use, what total amounts of the gross fossil fuel resources in the ground and industrial energies are necessary to establish and operate the system? See Figure 2.9.

Accounting Methods:

(1) Net Yield

The total of "external and process losses and unrecovered resource" shows how much energy, including fossil fuels in the ground, is made unavailable for a given output of energy product, given today's technology and economics. In other words, for a given output, one can see what resource in the ground and external energy inputs are required.

(2) Ratio

Ratio R_3: "Resource Net Yield Ratio"

$$\text{Ratio} = \frac{\text{Total ENERGY PRODUCT out}}{\text{Total ENERGY LOSS including "Unrecovered Resource"}}$$

Comment: This accounts for fossil fuels that are lost, damaged, or unrecoverable, given today's economics and technologies, as a result of the extraction and processing of the fossil fuels. It views the gross energy as the energy resource and the net as that which is made available to end users.

Each of these three accounting approaches has merit, and each or all may be used in any given analysis. This handbook is set up so that any or all of the three accounts may be analyzed.

2.1.4 Energy Quality

The quality of energy being processed or produced is important. In engineering terms, quality refers to physical characteristics which differentiate one British thermal unit from another. Energy is the capacity to do work. It takes various forms, and can be converted from one to another, such as heat, kinetic (motion), chemical (affecting heat as molecular structures change), potential (due to position or configuration of energy), electrical, nuclear, radiant (energy in transit through space). Coal is an example of chemical energy; when the hydrogen and carbon atoms in coal are combined with oxygen, forming water and carbon oxides, heat is released.

Energy quality has additional connotations, however. One measure of quality is economics; how much will society pay for a Btu of energy? Energy of different qualities is needed by society. Electrical energy is needed for lighting and electric motors; society no longer wants the water power and steam power of the earlier Industrial Revolution as motive forces for operating stationary mechanical equipment. Electrical energy has replaced these forms of energy. It is interesting to note that the price of electrical energy to the consumer varies from a fraction of a cent to well over ten cents per kilowatt-hour at present, but this range of prices is less relevant than the general fact of the societal demand for electricity. The quality of electricity is important, and certain characteristics such as transportation of electricity, electromagnetic reactions, ability to generate heat and light through thermal resistance or infrared radiation, etc., make electricity vital to modern life and industry.

The point of this discussion is simply that the expression of Btu's in absolute values does not provide all the necessary information about energy. Some indication of the form and quality must also be provided. Unfortunately, there are no standards or accepted criteria for describing quality. The description of the type of energy (gas, electricity, gasoline, etc.) is the first and most important indicator of its quality. More specific details may provide additional information. For a gas, the energy content in Btu per standard cubic feet is important. The precise chemical composition is also important. The presence of deleterious or undesirable constituents, such as H_2S, affects its quality and its price. Similar qualitative descriptors exist for other forms of energy. Their significance changes from time to time as social demands for quality change; sulfur in fuels was once much more acceptable than it is a present, for instance. Thus, the energy analyst may wish to describe the various energy streams in more detail than merely the amount of British thermal units.

2.1.5 Time Periods

Time frames associated with energy development are relevant to net energy analysis as previously mentioned in Section 2.1.2. The basic approach presented in the methodology of this handbook is to deal with a typical year of operations of an energy-producing system. The energy invested in the materials is required in the period of construction of the facilities. The materials have useful lifetimes; it is assumed that for a plant lifetime of n years, the average annual energy investment is simply the total Btu energy investment in

the materials divided by n years. It is also assumed that there is a typical design operating year in terms of energy inputs and outputs. In reality, some facilities such as a mine will reach productive capacity over a period of years, and may operate for years in a period of declining productivity. However, the analyst must select an average or typical year for the basic net energy analysis of this handbook.

Net energy analysis can be used to examine the time spacing of inputs and outputs. The life-cycle payback period of an energy investment can be examined; how long does it take the production system to pay back the energy invested in it? It should be noted, however, in any net energy analysis involving time spacing of energy flows, that a Btu is constant. Energy analysts do not discount Btu's as economists do with money, which does have a time value. If there is any time value associated with Btu's, these values should be measured with dollars. The potential energy, or chemical value, of a Btu does not change with time in general. It might be worth noting in an analysis if any degradation in energy quantity or quality is anticipated over time for a resource.

2.1.6 Regional and Site-Specific Analysis

Net energy analysis can be conducted at almost any scale or level. At the most detailed, an engineering analysis can be made of a single piece of equipment or a single chemical reaction. At the extreme other end of the scale, global energy balances, and net energy converted to biological and other energy from solar energy, have been conducted. Of concern to the Bureau of Land Management, however, are two levels of analysis which relate to the decision-making requirements of BLM and to the Environmental Impact Statement process based on the Guidelines of the Council on Environmental Quality.

The first level of interest is the site-specific analysis. In this case, the impacts and effects of a single action, relating to a well-defined project at a proposed location, and its alternatives at a comparable level, are to be examined. The action usually involves a group of components. The approach taken in this Handbook is to deal with each major component (and its alternatives) and with the totality of the components into the entire system which constitute the activity or action in question. Hence, each component is a module, as defined earlier, and each set of components is a trajectory, also as defined earlier, which includes all of the modules involved in the action being considered.

In this level of analysis, it is necessary to decide on the level of detail of a module, and the number of submodules which must go into the module. A single submodule may have a number of motors driving pumps, screens and crushers, and a number of heating and cooling actions. The approach of this handbook is to avoid that level of disaggregation, and to present data which is more general. However, in many cases, the data on a general operation such as coal preparation has been built up from more specific and detailed operations. The user of the handbook has the option of:

(a) using the data contained in this handbook, or

(b) obtaining new data from the engineers involved in the action being studied.

No two mines, energy conservation plants, or transportation systems are exactly alike. If it appears that a proposed operation might deviate significantly from that used in providing module data in this publication, the Bureau of Land Management should then require the submission of new data so that a module may be reconstructed or newly developed.

A regional analysis results from a cumulative set of site-specific analyses. In this respect, this handbook procedure requires that each site-specific action be analyzed, and that the regional effect be developed simply by summing the various site-specific effects.

2.1.7 A Short Glossary

Study Limits:	The portion of the real-life world being analyzed; the overall boundary of the entire system.
Trajectory:	A series of extraction, process, and transportation modules arranged to form an integrated energy-producing system.
Module:	A major operation which is one step in a trajectory.
Major Final Product:	The major trajectory product for which the energy-producing system is developed, i.e., electricity, natural gas, etc.
Principal Energy:	The main stream of energy being processed, which is always horizontal left-to-right flow in a trajectory and an input into any module.
Initial Resource Required:	The heat content of in-place resource which must be exploited to produce a given amount of Final Product.
Unrecovered Resource(1):	The heat content of energy initial resource which is unextractable due to current economics and commercial technology.

---

(1) For this item any energy unit (Btu, Joule, calorie, etc.) may be used. However, all items must be assigned consistent units.

Initial Process Input(1):	The heat content of resource subsequent to extraction by current commercial technology, which is processed to produce the Final Product.
External Energy(1):	Heat content of energy supplied to a module from other systems as (a) fuels and electricity and (b) energy sequestered in materials (energy of manufacture and/or heat content of material goods).
External Losses(1):	External energy which is used and lost in module operations.
Physical Losses(1):	Process losses due to spills, leaks, vents, flares, disposal, etc.
Internal Consumption(1):	Process losses due to use of some Initial Process Input to provide power, heat, etc.
Process Losses (1):	Loss of heat content from the Initial Process Input during energy production.
Direct Losses(1):	Heat content losses due only to energy directly associated with the energy-producing trajectory, i.e., goods, fuels, and electricity consumed by the trajectory modules.
Indirect Losses (1):	Heat content losses from other energy systems used to support or supply the selected trajectory.
Total Losses(1):	Sum of Direct Losses and Indirect Losses.
Final Product(1):	Primary Final Product at the point of end use.
R_1 - External Ratio(2):	Ratio of Final Product to Total External Losses.
R_2 - Process Ratio(2):	Ratio of Final Product to Total External and Process Losses.
R_3 - Resource Yield Ratio(2):	Ratio of Final Product to Total External and Process Losses and Unrecovered Resource.

(1) For this item any energy unit (Btu, Joule, calorie, etc.) may be used. However, all items must be assigned consistent units.

(2) See text for fuller explanation of net energy ratios.

Infrastructure Energy:	The energy needed by the workers, their families, and the associated community, for the production of energy from any trajectory.
Process Boundary:	The "fence" around the series of modules in the trajectory through which all external energy must enter. This process boundary separates the operations which are internal to the modules from those which are not controlled by the module operators and are generally part of the overall society which provides external energy, materials and the infrastructure needed for the module operations.

2.2 USES OF NET ENERGY ANALYSIS

Net energy analysis is only one of a number of analyses which enter into decision-making processing. Biophysical and sociocultural impacts and their mitigation must be considered. Economic factors must be appraised, and the final decision to proceed with capital investments will obviously be made on the basis of the profitability of the proposed action. Other factors, and costs related to them, will affect profitability. For example, the costs of revegetation, or of purchasing energy, enter into the economic analysis and effect on profit. However, these costs alone do not constitute the ultimate ramification of the project for the investors and operators.

Energy analysis by itself does not tell a decision-maker to proceed with a proposed project; it does not reveal the "bottom line." However, it does add an important dimension to the information used in decision-making. It does not replace economics. However, economics does not replace biological, social or engineering analysis. Food chains in an ecosystem cannot be quantified in terms of dollars. Human aspirations, pleasures, disappointments and psychological damage cannot be measured in dollar terms. The structural or thermal stability and feasibility of an engineering design cannot be developed in economic terms; they are governed by physical and chemical laws and properties. Net energy analysis describes the results of the application of the physical and chemical laws, and the engineering use of those properties, in the creation of a man-made project.

Economics uses many principles and practices which sometimes are created artificially, as rules for taxation. For example, some materials used in the production of energy are treated as capital expenditures and are depreciated at a rate which has no relationship to their useful life. Other materials are treated as expenses. For all materials, the energy needed for their production is hidden in economics.

Economic forces may mix national policies with factors of supply and demand. For example, when the Organization of Petroleum Exporting Countries (OPEC) has increased or decreased oil prices per barrel, partially in response to oil demand levels, partially for cash flow reasons, partially for national political purposes, the Btu per barrel of oil has remained constant. Also, even though inflation has changed the values of various national currencies,

inflation has not altered the energy defined as a British thermal unit or a kilowatt-hour.

A great many disparities between energy analysis and economic analysis can be identified, such as market imperfections in economic behavior. Some similarities can be identified. Also, the engineer designing an energy production system uses both engineering analysis, to make sure that the system will work, and economic analysis, to make sure that it will be the most profitable operation that could be designed. It is not the purpose of this handbook to define energy-economic interactions, to present methods for economic analysis, or to compare energy analysis with economic principles.

One of the first uses of net energy analysis is simply to quantify the energy needed for the action, by type. Thus, it can serve as a warning for those who procure or purvey the energy needed to make the entire system work. This may be especially important in regional studies, where a large number of energy-intensive development could strain the existing systems which provide energy, or could cause competition between various energy users for limited supplies of fuel. Authorities could at least be alerted to the potential problems, and could take mitigative steps, if energy information is included in the EIS.

Second, comparative analysis can be conducted. For various alternatives, the quantities and types of energies can be compared. The three energy accounting methods previously discussed can be used as desired. The analysis and comparsons can be at the level of sub-module, module, trajectory or region (different groups of projects). The conclusions to be drawn, and the decisions to be made, as a result of such comparisons, will vary from case to case. All else being equal, it seems wise to seek an alternative which has the potential for minimizing energy consumption or especially consumption of petroleum products, given the nation's degree of dependence on foreign sources of petroleum. Or, it may be more desirable in some cases to seek an alternative which might avoid construction of new electric transmission lines if such lines could impair scenic quality or have other adverse effects.

Comparisons on the future availability of energy are often difficult to make, due to the uncertainties and unknown variables in the problem. New future supplies can usually be obtained, and there may be excessive supply capacity available which can be devoted to a project or a set of regional actions. The excess capacity may be contingent upon the effectiveness of conservation measures or the availability of substitute energy forms (with both physical and economic availability as factors). The forecasting of local or regional supply-demand balances and economics is a complex matter, well beyond the scope of this handbook. Suffice it to say, however, that the net energy analysis plays a role in identifying energy demand.

Energy conservation studies and policies can grow out of net energy analyses. The intent of the Guidelines of the Council on Environmental Quality is to bring about energy conservation. This matter must be approached judiciously; economic and technological feasibility should not be distorted for the sake of the philosophy of energy conservation. On the other hand, economics and engineering analysis does not universally produce optimum energy efficiency or conservation, for a variety of reasons. The theoretical optimization may require changed lifestyles, development of new technologies,

massive economic tinkering, or other actions which are well beyond the ability of engineering, economics and politics to bring about. However, net energy analysis can serve as a point of departure for conservation analysis, because it does identify and compartmentalize the many inputs and outputs of energy in a system, including indirect energy, losses of energy, and external demands for energy in the supporting infrastructure.

Resource utilization and conservation can also be identified by the use of net energy analysis. The third energy accounting system previously discussed enables the analyst to address this issue. The net energy analysis may serve only as a point of departure for more intensive studies on methods and economics of maximizing resource recovery. The specific details of possible resource recovery improvements are highly site-specific, and depend on economics and technology which vary from case to case. In this handbook, general information on typical resource recovery is presented. The analyst is given a methodology in this handbook for pursuing specifics of resource recovery efficiencies and improvements, should this be desired, for any particular case.

Another use of net energy analysis is in identifying the proportion and quantity of critical fuels in the total energy input mix. Petroleum products can be considered critical fuels. In some localized areas, natural gas may be potentially critical.

Trade-offs can be examined if net energy analysis is conducted. Increased energy losses versus improved environmental quality can be examined, for example. In trade-off analysis, disparate elements must be compared, but such an "apples and oranges" comparison is inevitable in decision-making. Net energy analysis helps rather than hinders this type of trade-off analysis. If all factors involved in trade-offs are not identified, then trade-offs are made on the basis of speculation. Siting trade-offs can also be examined with net energy analysis as one of a number of analytical tools. The net energy yields of alternative trajectories resulting from siting conditions could vary significantly. There are a variety of other potential applications of net energy analysis, all of which will add information to the economic and environmental information which results from other studies associated with the proposed development or action. As previously mentioned, energy "pay-back" and other time-related studies may be conducted. These may be especially valuable in studying supply and demand over time, especially if there appear to be any supply constraints. Time-related studies can show cumulative effects, such as the total quantities of critical fuels which might be consumed over a given time period.

Perhaps the most important use of net energy analysis is as a foundation for further engineering economic and policy analyses. Finally, to keep net energy analysis in the proper perspective, it is clear that factors other than energy balances must influence responsible decisions, and they will generally carry more weight. These factors include: (1) economics; (2) environment; (3) national security; (4) energy mix, end use efficiencies, and substitutability; (5) lead times; (6) transportation capacities; (7) institutional restraints such as governmental regulations and incentives; (8) availability of needed materials; (9) available water; (10) local attitudes and socioeconomic impacts; (11) employment needs; and (1) needs for energy.

2.3 DATA FOR NET ENERGY ANALYSIS

One of the major difficulties in conducting any net energy analysis is that of data availability and quality. This difficulty is not unique to net energy analysis, of course. A discussion of the most important aspects of data in net energy analysis follows.

2.3.1 Level of Detail

The analyst must decide on an appropriate level of detail for any net energy study. One criterion for such a decision is the cost of acquiring data. The cost increases rapidly as the level of detail increases for all projects. For existing technologies, the cost problem is not as severe as for new and undeveloped technologies. In the latter case, it is sometimes impossible to obtain detailed information without proceeding to final engineering. This step is normally not undertaken until major hurdles, such as financing, major Federal approvals, and so forth, have been passed. Hence, it is unrealistic to expect to obtain detail beyond that of preliminary engineering for new technologies. The degree of accuracy of such information will be low, also, as many decisions must be made for new technology development between the preliminary engineering and final construction.

An example of a new technology in this handbook is that of tar sands processing. There are no operating plants at present. Hence, the information contained in this handbook is based on preliminary research and development studies. Detailed information has never been developed.

Another facet of the consideration of level of detail is that of variation of detail between processes. In this handbook, for example, there is considerable detail on energy consumption, equipment and unit operations on coal slurry preparation. Yet, there is almost no detail on uranium enrichment by the gaseous diffusion process, even though the energy and materials expenditures for the enrichment are orders of magnitude greater than those of the coal slurry preparation. The reasons are that: (1) the focus of this project is on actions for which alternatives must be presented to the Colorado State Office, Bureau Land Management, and (2) the scope of this project precludes equal attention to all processes, especially those for which information has been restricted as in the case of gaseous diffusion uranium enrichment.

2.3.2 Quality and Accuracy of Data

A second major factor is the quality of data. To an extent, this relates to the issues involved in the level of detail of data. Obviously, preliminary engineering studies will be of lower quality than detailed final engineering.

Quality of data involves both precision and accuracy. Precision refers to the number of significant figures or digits with which a quantity is stated. Sometimes, precision is exaggerated when computations are not rounded off to number of digits appropriate to the quantities being used in the computations. For example, dividing 9.3 by 2.62 yields 3.5496183, but this should be rounded to 3.5, the same degree of precision which exists for the least precise of the two numbers being used in the calculation.

Accuracy refers to how well a quantity represents truth or conforms to reality. If a quantity is obtained from rough estimation or loose measurements, it will deviate from the truth. It can be overstated by representing it with excessive precision, i.e., by using more significant digits than warranted by reality.

The aforementioned aspects of level of detail, accuracy and cost of engineering estimates are related to the process of engineering estimates in the following Figure 2.10. The right side of the figure shows increasingly refined estimates, moving from left to right, and shows the accuracy and cost generally associated with such estimates. Precision will normally improve by several significant digits between the left and right columns of the types of estimates.

2.3.3 Generality or Specificity of Processes

The degree of generality of the various processes is relevant. No two mines or energy processing operations are identical. Consider coal-fired power plants, for example. The age of the power plant affects its efficiency; older power plants are less efficient in design than new power plants, and it has been found that actual efficiency continually declines from design efficiency as power plants age. The efficiency depends upon the use of the plant: is it baseload, spinning reserve or seasonal? The type and quality of fuel input affect its efficiency, as do the type and degree of stack gas cleanup. In the case of coal-fired power plants for this handbook, for the coal-electric trajectory, a modern baseload plant will be assumed as "typical," as described later in this handbook. For indirect energy inputs in the electricity system, typica electricity grid data will be used, because the grid contains a mix of generating plants and does not match the "typical" plant.

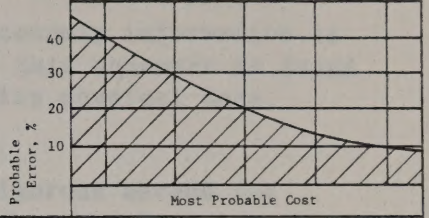
The data presented in this handbook represent those operations which are closest to the typical or which can be presented as a realistic range of operations. However, the user is cautioned that deviations may occur. The methodology enables the handbook user to acquire new data and analyze any case which represents a departure from the typical.

However, the use of data for a "typical" process constitutes a deterioration in the quality of the data, to the extent that the process being analyzed deviates from the that assumed as "typical." It is impossible to assign a value to the degree of inaccuracy from this problem without comparing the actual process with the "typical."

2.3.4 Data Sources

Very few of the numbers presented in this report come from measurements or engineering studies conducted by the project team of this study or from associtees at the Colorado School of Mines Research Institute. Most of the data are drawn from a wide variety of sources, as is evident from the list of references in this handbook. In some cases, several different sources of information will vary in their data for a particular process. One reason is that they may have used different ground rules, different system boundaries, or

TYPE OF ESTIMATES, ESTIMATING INFORMATION AND EXPECTED ACCURACY



	INFORMATION REQUIRED	Order of Magnitude Estimate	Preliminary Estimate	Budget Appropriation Estimate	Project Control Estimate	Definitive Estimate
	Percent of Total Engineering	2	5	15	27	40
Project Scope and Processes	Product and capacity, site location and requirements, utilities and service requirements, building and auxiliary facilities requiements, raw materials and product handling and storage requirements, project schedule.	○				
Site Preparation	Location of site		○	○	○	○
	General Description of site and facilities			○	○	○
	Subsoil investigation			○	○	○
	Location and dimension of site facilities			○	○	○
	Topo maps, general site preparation drawings (plot plan)				○	○
	Plant, road, railroad and other site preparation drawings					○
Process Flow Sheets	Description and sketches		○			
	Preliminary			○		
	Final				○	○
Equipment Selection and Layout	Preliminary equipment list		○	○		
	Final equipment specifications				○	○
	Preliminary general arrangement drawings			○	○	
	Final general arrangement drawings					○
Buildings and Structures	Preliminary sizes and type of construction		○	○		
	Preliminary structural designs			○		
	Foundation sketches			○	○	
	Architectural criteria			○	○	○
	General arrangements and elevations				○	○
	Detail designs, drawings and specifications					○
Utilities	Approximate quantities (steam, water, power)		○			
	Preliminary flow diagrams and heat balances			○		
	Final flow diagrams and heat balances				○	○
	Detail designs, drawings and specifications					○
Process Piping and Instr.	Preliminary P and ID's and criteria		○	○		
	Final P and ID's and criteria				○	○
	Detail designs, drawings and line lists					○
Electrical	Preliminary motor lists		○			
	Substations designs and specifications			○	○	○
	Preliminary power distribution single lines				○	
	Preliminary interlock, control and instrumentation				○	
	Final motor lists				○	○
	Final single lines, interlock control and instrumentation diagram					○
	Detail designs, drawings and specifications					○
Man-Hours	Engineering and drafting			○	○	○
	Labor by crafts					○
	Supervision					○
	QUOTATIONS FOR EQUIPMENT AND MATERIALS	0%	5%	20%	40%	75%

FIGURE 2.10
Accuracy of Estimates

accounting methods in performing their energy analysis. Another reason is that some may have been conducted at a higher level of detail and may have had access to more accurate information. A third reason is that processes and energy efficiencies have improved over time, and some older energy studies may be somewhat obsolescent. Fourth, some of the processes studied may not have been "typical."

Some of the analyses done by others have utilized economic information as a proxy for actual physical data. Further discussion of this approach is found elsewhere in this document. It is less accurate than using physical data, however.

The project team for this handbook did not have a rigorous method for evaluating the quality of data from various sources. It has not been possible to inquire into the factors affecting data quality for every source of data. The project team has sought to compare and evaluate data and sources, and to select that which appears to be most accurate. Judgment by the project team has been necessary in assembling the data for this handbook.

Proprietary data has been made available to CSMRI in some cases. Where it is used in this handbook, it is presented in such a manner that it cannot be tied to a specific corporation, operation or data source. It is the opinion of CSMRI that the use of such data leads to greater accuracy and precision for data.

2.3.5 Data Problems: Summary

The data considerations discussed above lead to several conclusions.

First, it would be desirable to place confidence levels or quantitative indicators of data accuracy on all data used in net energy analysis. However, this is not possible for much of the data used in energy analysis.

Second, due to variations in levels of detail and the degree of departure from "typical" processes, inaccuracies in some major modules of a trajectory will greatly overwhelm the energy quantities of some minor modules, even though these may be calculated quite accurately. This phenomenon does not constitute a reason for ignoring the minor modules or for allowing gross inaccuracies in the data and computations involving those modules, however. If there are alternatives for the processes of such modules, it may be desirable to compare them, in which case accuracy is desirable. Also, seeking reasonable accuracy in the data and computations for all modules creates greater confidence in the accuracy of the overall system or trajectory analysis.

2.4 COMPUTATIONAL APPROACH

2.4.1 The General Approach

The computational methodology used in this handbook is not theoretically pure. It is intended to be practical and pragmatic, and to depart from theoretical perfection in the interests of simplicity when such a departure will not result in the introduction of significant numerical errors.

Another departure from pure theory lies in the calculation of the energy sequestered in the materials. If one were to calculate Ratio R_1, discussed early, then indirect energy used to produce materials should not be calculated. For example, assume that there is one ton of steel, which required 50,000,000 Btu of direct energy in its production, and that 20,000,00 Btu of this was electricity. There would have been an additional 40,000,000 Btu of electricity lost in generating the 20,000,000 Btu of usable energy. Ratio R_1 would not consider this lost indirect energy. However, in finding a Ratio R_3 for the system, all energy inputs are traced to resources in the ground, and the lost 40,000,000 Btu would indeed be included in the computations.

However, it is very difficult to segregate sequestered energy into direct and indirect energies in obtaining energy data on materials production.

2.4.2 Materials Computational Approaches

The "sequestered energy" in materials poses some philosophical issues which were briefly discussed earlier in this document. The quantification of this energy involves additional problems as regards the availability and quality of data. The computational methodologies for developing the sequestered energy of materials are determined by the available data. None are entirely satisfactory.

There are several different methods for determining the amount of energy sequestered in materials. The first and most direct method utilizes pure engineering analysis, identifying every step involved in extracting mineral resources, agglomerating, beneficiating, refining, producing raw materials, fabricating finished products, and constructing field facilities. The materials flows and energy inputs into each step are identified. Even with this method, assumptions must be made and sometimes various processes or plants must be averaged. Several studies have been conducted on a variety of materials. They are not entirely consistent, either in methodology or in numerical findings. For instance, some calculate the energy inputs as direct energy only while others calculate energy resources in the ground. Also, some of the analyses were performed several years ago, and do not reflect recent energy conservation measures or fuel switching. Lastly, the number of materials and industrial sectors is quite limited. Nevertheless, this engineering approach appears to yield the best data. The data are expressed in energy units per physical unit of product, such as Btu/ton of machinery.

Ideally, a pure engineering approach would have every step, with all materials and energy flows quantified, for the production of the erected or constructed equipment used in a module. The exact proportions of each material in each piece of equipment or segment of a plant would be known, and the number of units of each piece would be known. For example, the amount of rubber, copper, glass, grey iron, cast iron, carbon steel, special steels, etc., in each of, say, 10 100-ton bottom dump trucks in a mining operation would be known; also, it would be known how much energy would have been expended in converting these materials into motors, frames, tires, etc. and finally into the completed trucks delivered to the mining site.

This level of detail is not available nor is it really necessary. Sufficient information are available to enable reasonable approximations to be

made. The level of accuracy is consistent with that achieved in the energy process analyses themselves.

The second method relies on economic data. The heart of this data is the Census of Manufacturers surveys of energy purchases by each industrial sector. This information is broken down by Standard Industrial Code (SIC) by major cities and by states, as direct purchases of various fuels and electricity, in dollars and energy units, for 1954, 1958, 1962, 1967, 1971 and 1976. This information alone is of no use, as it does not identify the relationship of sectoral energy consumption to sectoral output, either in dollars or physical units. Also, the energy purchases are direct energy inputs and are not resources in the ground of all the indirect inputs into each sector. To overcome these problems, an approach has been developed at the Center for Advanced Computation, University of Illinois at Urbana-Champaign. This apprach utilizes the Census of Manufactures data with a 357-sector input-output table. It basically traces all energy flows, either as energy or as energy sequestered in goods and materials, between all sectors, using the Leontief input-output model as the basis.

There are a number of problems associated with this approach which lead to a lower confidence in the quality of the data compared to pure engineering data. First, the industrial reporting system and Federal data acquisition and analysis system for interindustry transactions, fuel purchases, and value added per sector are not precise. Some data must be estimated by the Department of Commerce. An illustration of this is that data are omitted from the Bureau of the Census report "Fuels and Electric Energy Consumed" if the standard error of estimate is greater than 20 percent; other confidential data are not shown in the report because disclosure tests for such information are not satisfied. Also, some of the data are estimated from other data and prior year data.

The use of the Leontief input-output modeling method and data involves additional assumptions and estimations. It is assumed that there is a unique energy intnsity associated with the output of each industrial sector. Dollar data are inferior to physical data but must be used because of inadequate physical data. Dollar data are more subject to economies of scale. Exports into the U. S. economy are ignored. These exports represent an energy input, but the amount cannot be accurately estimated. Additionally, errors in the initial data input into the I-O model may generate disproportionate errors in the modeling process in matrix subtraction and inversion. Accounting for secondary products from a sector is inexact. Input-output coefficients change over time and yet the model does not reflect this. These are all some of the main deficiencies with the use of economic data and input-output modeling techniques for energy analysis. Nonetheless, the approach has validity.

The Institute for Energy Analysis, Oak Ridge Associated Universities, has compensated for some of the inherent weaknesses in the University of Chicago analysis. One of these weaknesses in in the average price of products. For example, in 1967, the average price of all steel produced was $180/ton; however the range was from $100 for a ton of semi-finished carbon steel to almost $2,400 for a ton of stainless steel pipe. The University of Chicago coefficient is based on the average price, i.e., Btu's of primary energy per 1967 dollar of steel. However, the energy embodied in steel products is probably not directly proportional to the price. The energy embodied in a ton of stainless steel pipe is certainly not 23 times for than that embodied in the

semi-finished carbon steel. The ORAU approach estimates the energy intensities in Btu's/ton of product rather than Btu's/1967 dollar. However, ORAU utilized economic data rather than pure engineering data as previously discussed as the first approach in determining their Btu/unit of product figures. Basically, ORAU multiplies the University of Chicago Btu's/1967 dollars times 1967 dollars/ton to arrive at Btu's/ton.

The approach which has finally been used for this project involves a mix of several of the above methods and a wide variety of sources of information. To the maximum possible extent, pure engineering data are used. However, in some cases the data do not take a product all the way through to final fabrication. Therefore, estimates of the difference in energy between materials into the final fabrication process and finished products out are used as multipliers to the input data. Secondly, in using the ORAU data, certain discrepencies are obvious. For example, copper and aluminum wire have a lower Btu/ton energy intensity than the primary copper and primary aluminum form which the wire is fabricated, according to ORAU. This is an obvious error although the source of the error cannot be identified without further analysis. Another puzzling finding in the ORAU data is that mining machinery is approximately 50% more energy intensive than construction machinery. This seems illogical and inconsistent. Similarly, computing machines are almost two and one-half times as energy intensive as electric measuring instruments, and electric swithchgear are almost twice as energy intensive as motors and generators. Also, motor vehicles and parts are almost 50% more energy intensive than industrial trucks.

Hence, it is felt that the ORAU data must be used judiciously. One approach which was utilized in this project is to take several industrial sector energy intensities where logic and other data indicate that there should not be significant differences between the outputs of the various sectors. Then, the energy intensities developed by ORAU for these sectors are averaged and applied to all of them. Another reason for such averaging is that the level of detail used for materials in this project as regards the indentification of materials and their quantities in the processes and modules of the project is not as detailed as the ORAU disaggregation. For example, it is impossible to identify the actual quantities of sheet metal, switchgear, motors, generators, industrial controls, transformers, pumps, compressors, and pipe fittings for an oil shale processing module. Therefore, the ORAU data for all of these items were averaged and considered to be "electrical and mechanical equipment" energy intensities. Other averaging was used similarly.

Section 4 contains a more detailed discussion with actual data derivation and utilization for the energy embodied in materials. In summary, it is noted that there is no perfect method and that for any approach, data are highly reliable. The final approach used for this project mixes several different techniques and used for this project mixes several different techniques and uses data from different approaches as cross-checks and validation information. It is felt that the errors and inaccuracies on the energy of materials data of the project are tolerable and within the range of inaccuracies associated with other data of the project. It should be noted that, in general, the energy sequestered in materials is very small relative to the total throughput of Principal Energy of an entire trajectory. Hence, larger errors in the energy sequestered in the materials will not be influential in creating large

inaccuracies in the overall trajectory analysis. On the contrary, such errors will become insignificant and within the "noise" or error of estimates of the overall trajectory.

2.5 PRESENTATION OF ANALYTICAL RESULTS

One of the problems associated with net energy analysis is the amount of final data which can be generated and presented. It is possible to be overwhelmed with a large array of figures representing various inputs and outputs by fuel types of direct and indirect energy. The data can be presented as quantities of Btu's or as ratios, as previously mentioned. There are no commonly-accepted rules, guidelines or preferences regarding the final presentation of data. It is possible to recommend some guidelines, however.

First, it must be decided whether it is important to show energy inputs by direct input and indirect inputs separately or by the total of direct plus indirect inputs. (If indirect inputs are not in the study boundary, they are not in the final data regardless of the presentation format.) Second, it is necessary to decide if data should be shown only as total Btu's or as Btu's of each different type of fuel. Third, it must be determined to isolate any specific input such as infrastructure energy, raw resources, or materials energy. Fourth, it it necessary to decide on a presentation format of ratios or quantities.

The methodology of this handbook allows for final data presentations using any of the above forms. Data can be traced through the various steps of the methodology in detail and thus can be presented in detail or in various aggregate totals. However, it is strongly recommended that only a limited amount of data be presented as a result of the analysis.

2.6 COPRODUCTS AND BYPRODUCTS

There are a number of ways to calculate or assign the energy to coproducts or byproducts of a trajectory or module. Various investigators of net energy analyses have used different approaches. No method is perfect. However, several approaches and ground rules will be presented here.

First, it must be observed that for a coproduct or byproduct to be a product, it must have a market. Otherwise, it is a waste material.

The best method to split the Principal Energy Output between various coproducts would be to calculate the actual energy flows in each step of a process and determine from principles of thermodynamics how much energy is affected every time a chemical reaction or physical separation takes place in the product stream. This amount of enegineering analysis is seldom possible in net energy analysis, and has not been used in this handbook.

A second method is to assign all energy to the main fuel products and no energy to non-fuel byproducts.

A third approach is to assign the energy of combustion to all products; those which have no energy of combustion or full value (such as nahcolite) would be assigned no energy value.

A fourth approach is to split the principal energy inputs to the energy product outputs, and for non-energy products, assign the energy value which would be required to produce those materials from traditional or conventional sources. This assumes that a certain amount of energy elsewhere in society would be displaced by the production of the byproduct; hence, that "displaced energy" should be assigned to the byproduct, even though a much smaller amount of energy may have been used in producing it in the trajectory under consideration.

One problem with the various approaches is that each module and the overall trajectory should be in balance. That is, inputs of energy should equal outputs of energy. The "displaced energy" approach violates this principal.

For the purposes of this handbook the approach which is used is to assign all the energy in the principal energy input stream to the energy products and no energy to the non-energy byproducts. This is not thermodynamically or chemically precise, but the purposes of this net energy analysis are for policy, not chemical, analysis. It is noted that the approach used in developing an energy balance for a module does not consider non-energy inputs such as air, water, sulfur in feedstocks (principal energy inputs), etc. Hence, stoichiometry is not an analytical method in this type of net energy analysis.

2.7 UNITS OF MEASUREMENT AND NUMERICAL NOTATION

The common English measurement units are utilized in this handbook: British thermal units, pounds, etc. Energy values are expressed in engineering notation; i.e., as ten to some power which is always in multiples of 3, such as 10^6. These units are:

thousands = 1×10^3 = 1,000
millions = 1×10^6 = 1,000,000
billions = 1×10^9 = 1,000,000,000
trillons = 1×10^{12} = 1,000,000,000,000

Thus, an energy value might be 250 trillion British thermal units, and would be expressed as 250×10^{12} Btu.

3. INSTRUCTIONS FOR USE OF HANDBOOK

3.1 INTRODUCTION

As described in the preceeding chapter, the method used in this handbook involves the construction of trajectories, the analysis of direct energy and materials in individual modules of the trajectory, the application of indirect energy to the modules and social infrastructure of the trajectory, and the final calculations of trajectory energy. If regional analysis is also conducted, the site-specific trajectories must be totalled to provide the regional analysis.

The methodology described in this section is intended for use for any energy system or regional combination of energy systems. In a later section, the best available data are presented for specific modules and for the general indirect and materials energy inputs. Using that data with the general methodology presented in this section, any trajectory or regional analysis can be developed. There is one major caveat to this statement, however, and it is in regard to the data presented later on. In some cases, the data for specific modules are either non-existent or so general that the Bureau of Land Management should require the submission of new data, developed specifically for the proposed action, rather than relying on the general data. This caveat is discussed further in the data section of this handbook.

The following general methodology is presented on a step-by-step basis; the first two general steps are presented in this chapter, then, following a discussion of oil shale modules and data in Chapter 4, an example is given in Chapter 5 on a step-by-step basis. It is not structured as a computer model (although this approach could be developed from the handbook) and is designed to avoid complex mathematical calculations. This approach emphasizes the use of diagrams and standard forms with relatively simple arithmetic. The diagrams and forms contained in this handbook are for universal application, and the diagrams presented in this chapter are general and are for illustrative purposes. When an actual specific application of the handbook is undertaken, the diagrams presented in the following section should be used, either as shown or with modifications should a proposed action differ from that described in the next section.

The handbook is to be used as follows, then:

(1) proceed through the step-by-step method presented in this chapter, and in Chapter 5, and

(2) at appropriate locations in the steps, insert the data from Chapter 4 or from the proposer of the action should the data in the next section be inadequate or inappropriate.

3.2 GENERAL CONCEPT OF TRAJECTORY DESIGN

The purpose of this step is to ensure that the issues associated with net energy analysis are clearly identified, and that the overall study limits are properly related to these issues. For example, referring to the previous section, the amount of energy utilized by the supporting infrastructure may not be an issue. If this is the situation, then the infrastructure energy should

not be included. It may be that infrastructure energy is considered as important to the study, but there is no need to differentiate that energy from the other energies in the proposed project. If so, this step is the place for such a decision.

The following activities are needed:

(1) Describe the issues. Referring to Chapter 2 of this handbook, determine which of these energy factors are important and are to be addressed in the analysis:

Direct External Energy Inputs
Indirect External Energy Inputs
Materials Energy Inputs
Resources in the ground at the start of the trajectory
Resources Recovered and Unrecovered
Form of Final Project (i.e., the trajectory and modules)
Infrastructure Energy

(2) Describe, in text form, what might be included in the boundary and, of these items, what is to be actually included in the analysis. The boundary could include water supply, infrastructure, indirect energies, materials, resources in the ground, and other elements; see Figure 2.6. The data methodology of this handbook excludes certain items such as ecological energy, as shown in Figure 2.6.

(3) Draw the trajectory with:

Modules, inputs, outputs and losses
Process boundary
Description of study limits: items included and excluded
Locations where initial data are needed

Figures 3.1a through 3.1e are examples of this step, proceeding sequentially from the simplest trajectory with the fewest elements included, to a complex trajectory with a maximum number of elements included. The latter will enable the analyst to develop accounting methods or ratios one through three for those issues and to include infrastructure and materials energy and unrecovered resources. These figures are presented here for a general oil shale system.

Figure 3.1a is Case A, the simplest case. The study limits include external energy as inputs into the modules shown, and recoverable resources in the ground. Excluded are: indirect external energy, materials energy, infrastructure energy, and unrecoverable resources. For Case A, two issues can be addressed. These are Issue 1, how much industrial energy must be invested in a system relative to its final product, and Issue 2, how much industrial energy and initial recovered principal energy must be invested in a system relative to its final product. Further, the invested energy is limited to direct external energy, not to the indirect external energy traced back to resources in the ground. Infrastructure energy, which is an indirect energy, is not included. Thus, the external energy can be identified and quantified as gasoline, diesel, electricity, natural gas and other products, but cannot be identified or quantified as crude oil needed to make gasoline or diesel fuel,

coal or other fuels needed to make electricity, hydropower converted to electricity, etc. The initial oil shale resource in the ground is not relevant to this case, either; only that shale oil which is actually mined is quantified.

Note that external energy comes from outside of the process boundary, and principal energy leaves the boundary of the process to be refined and marketed for consumption as various fuels.

Data are needed for each module as indicated by the asterisks on Figure 3.1a. In the "mining," "surface retorting" and "upgrading" modules, data are needed for the efficiencies of these operations. For example, if the surface retorting process cannot utilize shale fines which are produced in the crushing component of the mining modules, then these fines must be rejected. This diminishes the Btu flow of the principal energy moving from left to right through the mining module. In the "retorting" and "upgrading" modules, some of the principal energy is lost (as waste heat, for example) or used within the module as process energy in lieu of external energy.

It is further noted that the "convey raw material" and "transport" modules do not include asterisks for data needed within the modules. This is because it is assumed that 100% of the principal energy input into the module from the left leaves the module as output on the right. In other words, there are no losses or uses of principal energy in these operations. For these two modules, the only losses are the external energy inputs, which are inevitably lost to society once they are used to drive the operations of these modules.

Also, it should be pointed out that energy losses in "spent shale disposal" represent the external energy invested and possibly some unrecovered hydrocarbons in the spent shale from the retort and unusable shale fines from mining and crushing.

The data needed for the initial input of recovered oil shale in "mining," as well as the mining module output to "retorting," must include tons of shale and Btu per ton.

Figure 3.16 is Case B, which changes the study limits to include both direct and indirect external energy, and all resources in the ground, both recovered and unrecovered. The study limits do not include materials energy or infrastructure energy, however. Case B allows the quantification of Issue 3, using Accounting Method 3: what total losses of external energy and resources in the ground occur to achieve a product output? Note that indirect external energy resources are quantified as resources in the ground, i.e., as crude oil, coal, etc., rather than as gasoline, diesel, electricity, etc. The only consistent logic for Case C is to include recoverable principal energy resources in the ground for both the indirect external energies and the principal energy which flows from left to right through the trajectory.

It is not logically inconsistent to exclude materials and infrastructure energy as shown. Later cases will include them.

As will be addressed later in this handbook, and as indicated in Section 2.1, infrastructure data involves both population data and per capita energy use.

The reasons for including the recoverable resource as an initial input into the "mining" module are, first, to quantify any materials-handling conditions which require external energy inputs (such as disposal of unusable shale fines), and second, as the initial principal energy input in Issue 2 as quantified using Accounting Method 2. This number is not actually used in Accounting Method 1 for Issue 1. This box is shown with a dashed border , as it is not a true module. The reason is that no operations take place in the box, as they do in typical modules such as mining. The resources in ground are shown as a separate box at the start of the trajectory to allow for conceptualization, and later on, for calculation of recoverable and unrecoverable fractions of the resource.

It should be noted that a variation of Case A, Issue 2, could be developed by including the initial process energy which becomes input into the direct external energies. Thus, direct gasoline purchases would be traced back to the crude oil inputs into the refineries which produce the gasoline, but not traced all the way back to resources of crude oil in the ground. This variation would be entirely logical and consistent. However, it is not included in this handbook because it would add another level of complxity, especially in that two set of indirect external energy data would be required. One set would be for the initial process inputs into external energies; the other would be for the resources in the ground as inputs into the external energies. Because BLM has expressed an interest in resources in the ground needed to produce energy products, the computational methods in this handbook include this concern, but do not include the possible variation discussed in this paragraph. The next case includes resources in the ground.

Figure 3.1c shows Case C, which is a variation of the trajectory used in Cases A and B. The variation is to include a power plant, fueled by a portion of the system principal energy, within the process boundary. The effects of this would be: (1) to reduce the amount of direct external energy which must be purchased, and hence, for Issue 3, the indirect external energy resources in the ground; (2) to reduce the losses from the retorting module; (3) possibly, to alter the principal energy quantities flowing into the "upgrading" and "transport" modules, and hence the amount of Final Product. This latter effect would thereby reduce the direct and indirect energies needed in the "upgrading" and "transport" modules.

Case C could occur with the Paraho direct retorting process or with a MIS process, with low-Btu gas being taken from the retort into a turbine-generator. The availability of suitable turbine technology, and the overall economics of this option, will finally determine if this trajectory will actually be used in practice.

Other "on-site" energy use, or recycling of principal energy from one module into others, either with the conversion losses shown in Case C or without such losses, could occur. The upgrading module could produce diesel fuel which would replace external energy in the mining module. Spent shale containing carbon could be used as fuel in a fluidized bed boiler of an on-site power plant, given development of this technology. In this case, a materials flow would occur from the retort to the on-site power plant and from the power plant to spent shale disposal. Since these flows all occur within the Process Boundary, it is essential to show them explicitly to ensure correct quantification.

The on-site power plant efficiency is important, because it determines how much of the principal energy stream which is bled off into power generation will end up as electrical energy, replacing purchased external energy. It is conceivable that the power plant would use both principal energy and purchased external energy; if so, this condition would have to be shown on the trajectory.

The explicit treatment of this "recycled" energy between modules is essential whether one is dealing with Accounting Method 1, 2 or 3. The modules and flows discussed for Case C could occur in Cases D and E which follow.

Figure 3.1d presents Case D, which is exactly like Case B except that the energy sequestered in materials is included within the study limits. This is shown on the figure, labeled "M", as an Indirect External Energy Input. Referring back to Figure 2.2, it can be seen that the energy expended to make materials used in the system is always indirect energy. For purposes of simplicity, this is always treated as energy resources in the ground in this handbook. Hence, materials energy should never be included in Case A, Issue 1; to do so would be logically inconsistent.

Figure 3.1e presents Case E, which is exactly like Case D except that infrastructure energy I is included within the study limit. This is always considered to be an indirect energy input. For simplicity of calculations in this handbook, it is shown as an aggregation of the entire infrastructure needed for the whole trajectory, rather than being calculated on a module-by-module basis.

Another case could be constructed including infrastructure energy, as in Case E, but excluding materials energy which is shown within the study limits of Case D. To do so seems illogical, however, because much of the infrastructure energy is that sequestered in the materials used in the houses, cars, appliances, foods, and other purchases of the infrastructure which supports the system of the trajectory. This is, in effect, "life style" energy. Accordingly, it is recommended that a case including I but not including M should not be pursued.

For all of the cases presented, water resources have not been shown in the interests of simplification of the examples. It may, in actual practice, be necessary to add a water resource module (pumping, storage, etc.) either outside of or within the process boundary. In all cases, the methodology of this handbook excludes ecological energy and other factors which are identified on Figure 2.6 as being consistently excluded from calculations.

What determines the size and contents of a module? How many modules should there be in a trajectory? An oil shale retorting operation with its pollution controls may have dozens of different major pieces of equipment and unit operations. Each one could be drawn as a module, and, if one were doing detailed engineering design, should be drawn as a module. However, the purposes of the net energy analyses which are the subject of this handbook are much broader and are at a more general overview level. Therefore, each module contains a number of unit operations and requires a variety of equipment.

The next step deals with module description. After one goes through that step, it may be desirable to return to this Step 1 to adjust the picture of the entire trajectory. It may be desirable to add modules or combine two (or more) modules into one. This is a judgmental matter. However, it is felt that the modules as described in Section 4, and the trajectories, are at the right level

of detail and disaggregation for a net energy analysis which meets the purposes of BLM. Each module is a major operation which can be varied from project to project, and which can be treated as an entity even though it has a number of steps or elements within it. The discussion of the next step will treat this matter in greater detail.

3.3. GENERAL CONCEPT OF MODULE ANALYSIS

The purpose of this step is to draw each module of the trajectory with the major elements of the module, and to define and quantify the inputs and the outputs of the module.

The first concern is in defining the major elements and the scope of the module. As mentioned, Section 4 presents the general modules recommended for use. However, new projects, processes or systems may be presented to the user of the handbook which will dictate a different number of modules with different steps and scopes.

In identifying modules, include the major groups of processes as modules; minor processes can be included as elements within a module. The minor elements could be treated as individual modules, but this merely increases the computational complexity. One ground rule for locating elements or unit processes is that the group of unit operations causes a certain loss of principal energy; changing this unit operation group could result in change in the principal input-product output loss ratios of energy of as presented in the "typical modules" of this handbook.

To illustrate this point, if there is a loss of oil shale in fines in secondary crushing shown in a retorting module, and if it is decided to move "secondary crushing" from the retorting to the mining module, the loss of fines from secondary crushing would then affect the principal input-output-loss ratios of both modules. The analyst would have to adjust the calculations from the "typical modules" for this condition. Secondary crushing is treated as an "element" in this case because it could be moved to another module.

The next activity is to draw the module, list the elements, and describe the inputs and outputs. This will be done in this step in several sequential substeps, moving to increasing complexity of inputs, in order to be consistent with the options or cases of step 1. In other words, if the issues and accounting methods for the project do not include materials energy, then the module inputs should not include them. The following figures show the method of proceeding through the different issues.

It should also be noted that the format must be uniform for each module in a trajectory. The reason is that it is necessary to add the energy inputs for all modules to get a trajectory total. Non-uniform formats between modules might lead to an "apples and oranges" summation.

Figure 3.2a shows Case A for a module, consistent with Case A of figure 3.1a for the entire trajectory. It shows the following information:

(1) Principal Energy entering the module from the left, to be processed in the module activities. By "processed," it is meant that the energy would be transported, converted from one form to another, or

extracted from its ore. The information needed includes the type of energy or energy material (such as coal, oil shale, electricity), the quantity and units (100 tons, 1 x 10^6 kwh, etc.), the Btu/unit (2 x 10^6 Btu/ton, etc.), and the Btu input. The latter is obtained by multiplying the quantity and units by the Btu/unit; for example, 100 tons coal times 2 x 10^6 Btu/ton = 200 x 10^6 Btu total. It is assumed that the tons input, and hence the total Btu, are on an annual basis.

(2) Principal Energy Lost, exiting from the bottom of the module as waste energy and henceforth considered unusable to society unless technology and/or economics change. (For example, if the Principal Energy Lost is waste heat, cheaper and better heat exchangers could enable this loss to altered and the energy used within the process, or between modules, to replace purchased External Energy.)

(3) Principal Energy Output; this is an input to the next module to the right unless this module is the last module at the right-hand or downstream end of the trajectory, in which case it leaves the Process Boundary of the trajectory as the Final Product. It should be noted that the form of the energy may change from that which is input to that which is output; for example the Principal Energy Input may be coal and the Principal Energy Output may be electricity.

It is important to note that there may be several outputs. There may be retorted shale oil and low-Btu gas from a retort, for example. These must be identified and quantified. Sometimes co-products or by-products will be non-energy materials. For any co-product or by-product output, it is sometimes difficult in net energy analysis to make an accurate split or assignment of the output energy to each product. Further discussion of this matter is found in subsequent Sections.

(4) The Process Efficiency within the module, which determines the split of Principal Energy Input to Principal Energy Output and Principal Energy Lost. Any operation on energy (except simply transporting it) will involve a loss of energy. For example, a typical modern base-load coal-fired power plant is about 39% efficient in converting coal to electrical energy. The Process Efficiency number would be 39%; for 100 Btu of Principal Energy Input, 39 would be Principal Energy Output (39% of 100), and the balance (100 input minus 39 output) of 61 Btu would be Principal Energy lost.

(5) Any Principal Energy Output which is used within the process boundary, outside of this module. See Figure 3.1c for an illustration, and Section 5 for a discussion, of an example in which a product is sent to an on-site power plant and used within the process boundary. In most cases, this item (5) will be zero.

(6) Direct External Energy, broken down by element (rows in figure) and fuel types (columns in figure). The sum must be found for each fuel type for the energy inputs by element. This energy must not be

confused with Principal Energy; Direct External Energy is not processed in the module but rather, it "drives" the module. For example, if the module were a diesel-powered unit coal train, the Principal Energy would be coal and the Direct External Energy would be diesel fuel. In nearly all cases, the Direct External Energy is purchased from outside the process boundary (see Figure 3.1a). In some cases, such as "electric, on-site", it may be generated from within the process boundary (see Figure 3.1c).

The elements, as previously discussed, are the major steps in the module. For example, the "coal mining" module may include elements of "mine," "primary crushing," "haul to preparation plant," "clean and convey to load-out."

(7) External Energy Loss, which is equal to the sum of all external inputs. It is assumed that all external energy inputs do their work in "driving" the module operation, and then are so degraded and diffused as energy that they are no longer useful to society. It is noted that, for each module, all inputs as total Btu's must equal all outputs; i.e., there must be an energy balance. Item (1) must equal the sum of (2), (3) and (5). Item (7) equals item (6). Therefore, inputs (1) and (6) equal outputs and losses (2), (3), (5) and (7).

This case is appropriate for use with Figure 3.1a, Trajectory Case A, to answer Issues 1 and 2 using Accounting Methods 1 and 2.

Figure 3.2b displays Case B for a module, consistent with Case B for a trajectory as shown in Figure 3.1b. This figure is similar to Figure 3.2a; however, Indirect External Energy is now added. This is shown as item (8) on the figure, "Total External Energy as Resources in Ground." It is disaggregated by type of resource, i.e., crude oil; natural gas; coal; etc., which are the columns of this item, and by each Direct External Energy type, i.e.: Electric Off-site; Gasoline; Diesel; etc., which are the rows of this item. Each number of item (8) is obtained by multiplying:

(Sum of Btu's for each energy types, item (6) x
(Indirect Energy Multiplier from Section 4.3.3)

The number entered in each cell of item (8) represents the sum of the direct energy and the indirect energy for each fuel type and Direct Energy type. It is not necessary to add the sums of items (6) and (8), because the multiplier automatically takes care of this. The Total External Energy for each energy type is the sum of each column, and is entered at the bottom line of each column in item (8) as "Sum, item (8)."

This figure also is expanded from Case A to show the recovery and loss of the Principal Energy resources in the ground, as shown to the left at the bottom of the figure. This is only applicable to the first module of a trajectory, and should be ignored for all modules that are downstream from the first module. The box to left is labelled item (11), "Resource Recovery." It contains provisions for data on the total initial resource in the ground, the Recovery Efficiency as a percentage, and the Unrecovered Resource. The total initial resource times the efficiency gives the Principal Energy Input, item

(1). The initial resource minus item (1) equals the unrecovered resource. For example, if the initial resource in the ground were 1,000,000 tons of coal @ 20,000,000 Btu/ton = 20×10^{12} Btu, and it was subjected to surface mining with a 90% efficiency in recovery, then (0.90) (20×10^{12} Btu) = 18×10^{12} Btu would become Principal Energy, item (1), and the remainder (0.10) (20×10^{12} Btu) or (20×10^{12} Btu - 18×10^{12} Btu) would be the unrecovered resource of 2×10^{12} Btu.

Figure 3.2c carries this sequence of module development to the final case, Case C, which now includes the energy sequestered in materials. This is shown as item (9) on the figure. The rows provide for the identification of each material, such as "concrete" or "copper," and its quantity and the columns provide for the energy resources in the ground, by type of energy resource such as "crude oil" or "coal," needed to produce that resource. The bottom line of each column is the sum of all energy resources of that type needed to produce all the various resources needed to produce the materials for the module construction and operations ("Sum item (9)").

Item (10) on this figure is the Grand Total, External Energy Inputs as resources in the ground. It is obtained by adding, for each energy type, the sums of items (8) and (9).

For items (8), (9) or (10), if one desires the total Btu's for all energy types (crude oil plus coal plus natural gas, etc.), all that is needed is to add the bottom lines of each energy type for that item.

This completes the general methodology for developing the various inputs and outputs of a module. In Section 4, descriptions of standard modules are given for various mining, processing, coversion and transportation modules, such as "coal surface mining," "direct heated oil shale retorting," "slurry pipeline," etc. Data for each standard module are presented on forms which are identical to Figure 3.2c. The standard Principal Energy Output, item (3), is given on each of these standard module figures. In the next step, the means of combining modules into a trajectory will be developed; as each standard module is inserted into a trajectory, the standard numbers for all items are simply multiplied by a ratio of:

$$\frac{\text{actual module output}}{\text{standard module output}}$$

to give the actual numbers for the module in a trajectory.

3.4 DATA SUMMATION

The final task is to sum the data and present the results. The data for each module must be entered onto the trajectory diagram and all modules must be summed up as a trajectory. In actual practice, it is necessary to alternate between working on a module and on the trajectory, as will be clearly explained in Section 5 and the example of that section.

Finally, net yields for the entire trajectory, or sum of various trajectories in a regional analysis, can be determined.

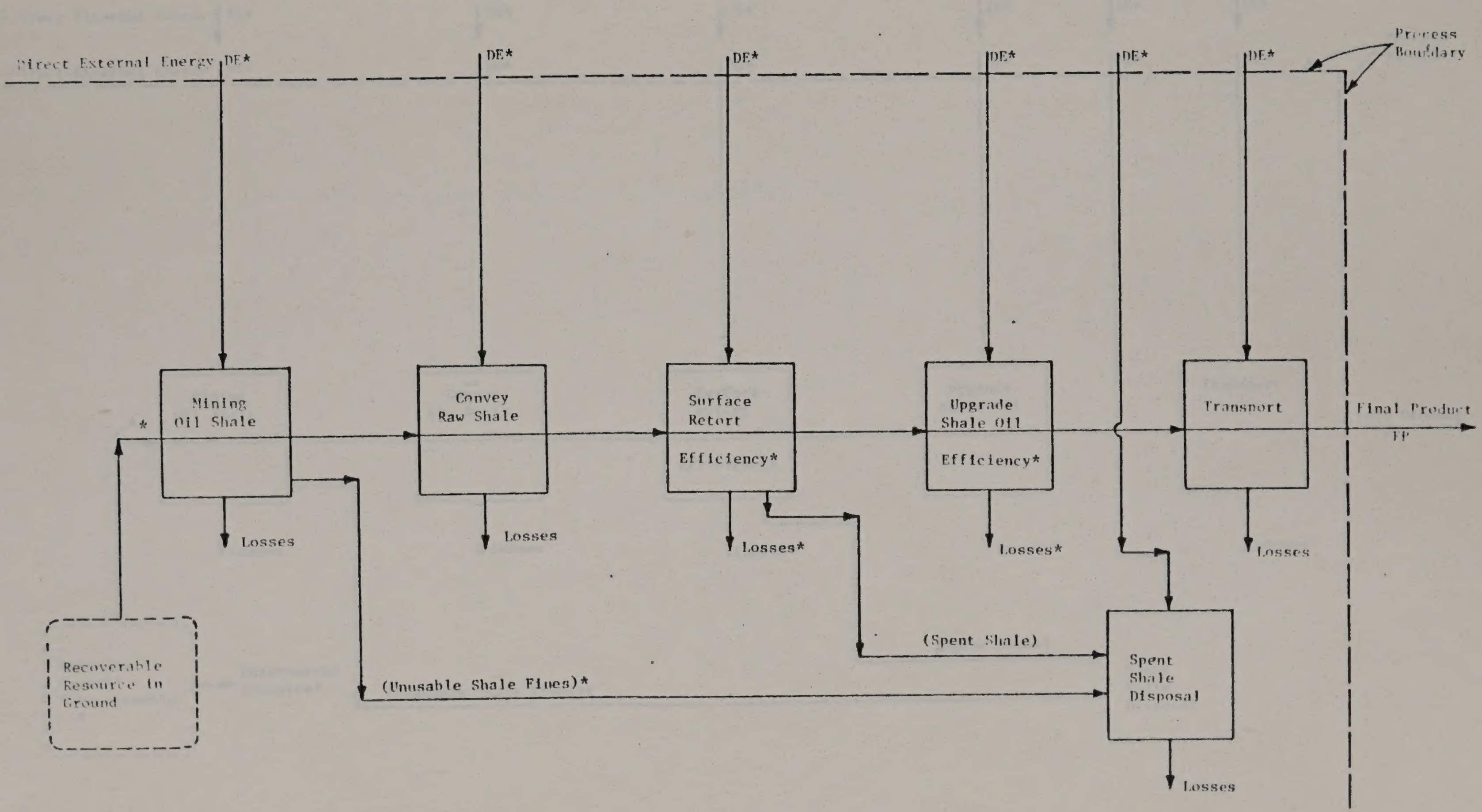


FIGURE 3.1a

General Method Step 3.2.1: Define Issues, Study Limits, Trajectory and Process Boundary

Example: Oil Shale Production, Surface Retorting

Case A: Trajectory: As shown — Data Required: Indicated by *

Study Limits: Included: Direct External Energy
Recovered Resources in Ground

Excluded: Indirect External Energy
Materials Energy
Infrastructure
Unrecovered Resources

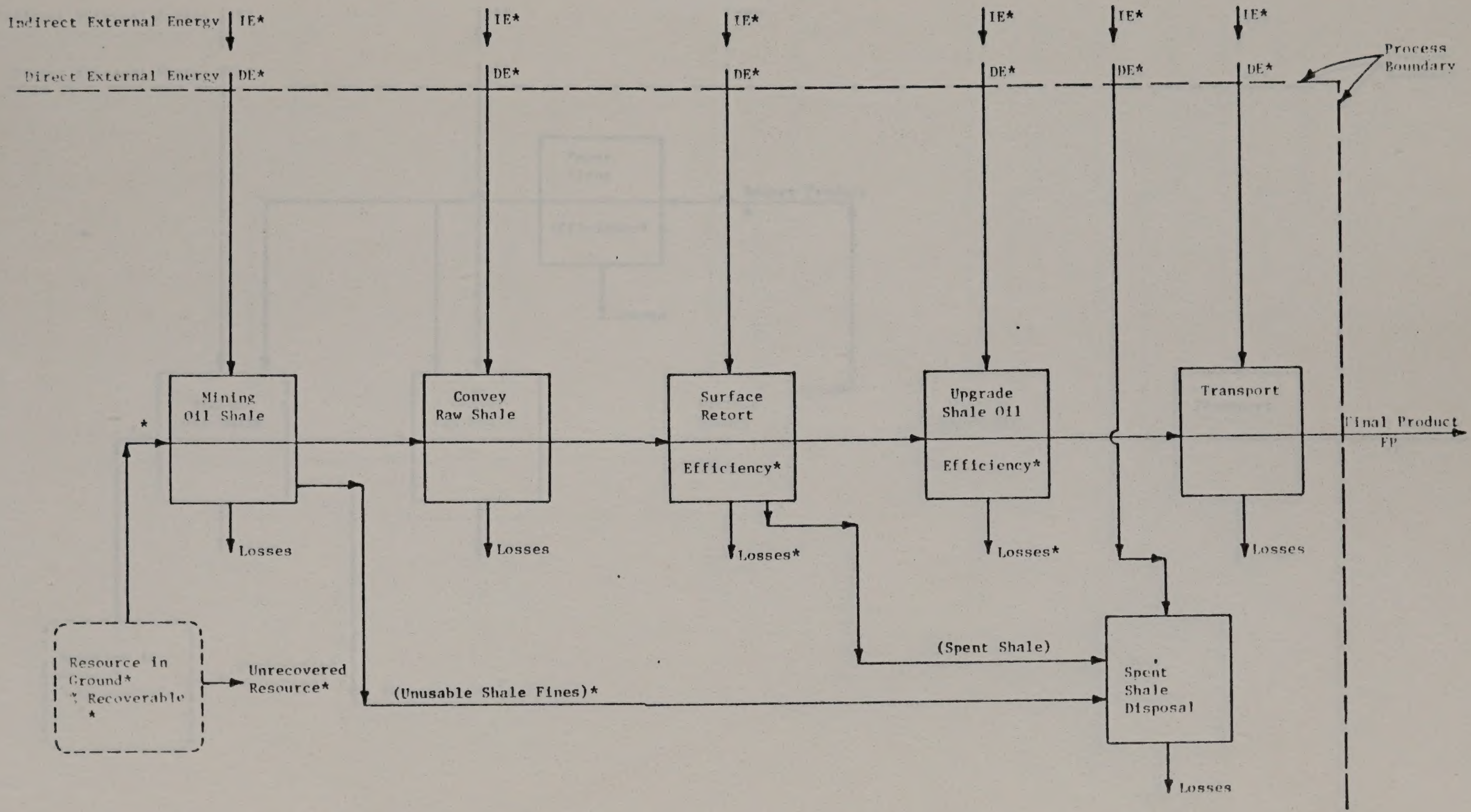


FIGURE 3.1b

Example: General Method Step 3.2.1: Define Issues, Study Limits, Trajectory and Process Boundary
Oil Shale Production, Surface Retorting

Case B: Trajectory: As shown   Data Required: Indicated by *

Study Limits: Included: Direct External Energy
Recovered Resources in Ground
Indirect External Energy
Unrecovered Resources in Ground of Principal Energy

Excluded: Materials Energy
Infrastructure

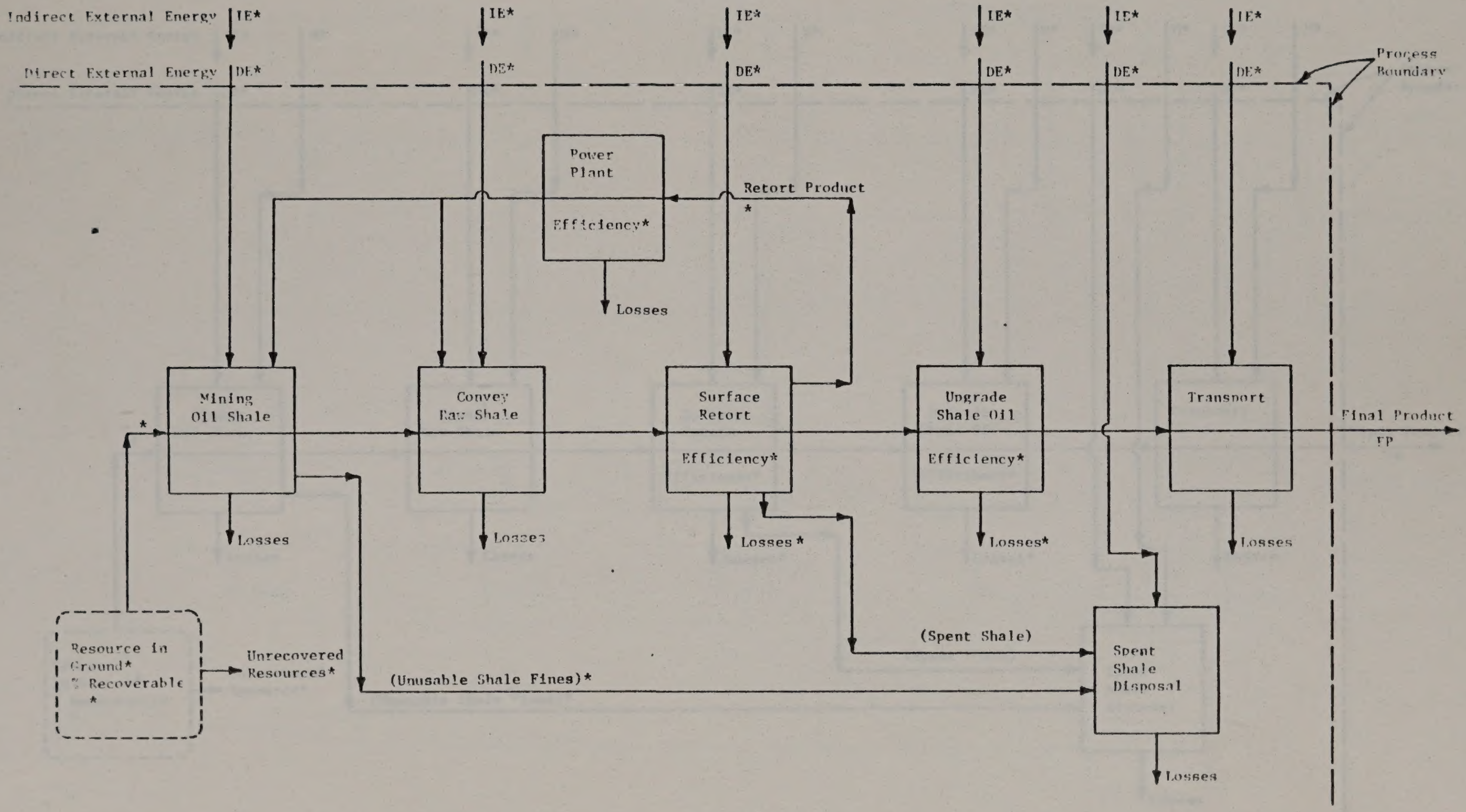


FIGURE 3.1c

General Method Step 3.2.1: Define Issues, Study Limits, Trajectory and Process Boundary

Example: Oil Shale Production, Surface Retorting

Case C: Trajectory: As shown, with "on-site" electricity generation

Study Limits: Included: Direct External Energy
Recovered Resources in Ground
Indirect External Energy
Unrecovered Resources in Ground of Principal Energy

Data Required: Indicated by *

Excluded: Materials Energy
Infrastructure

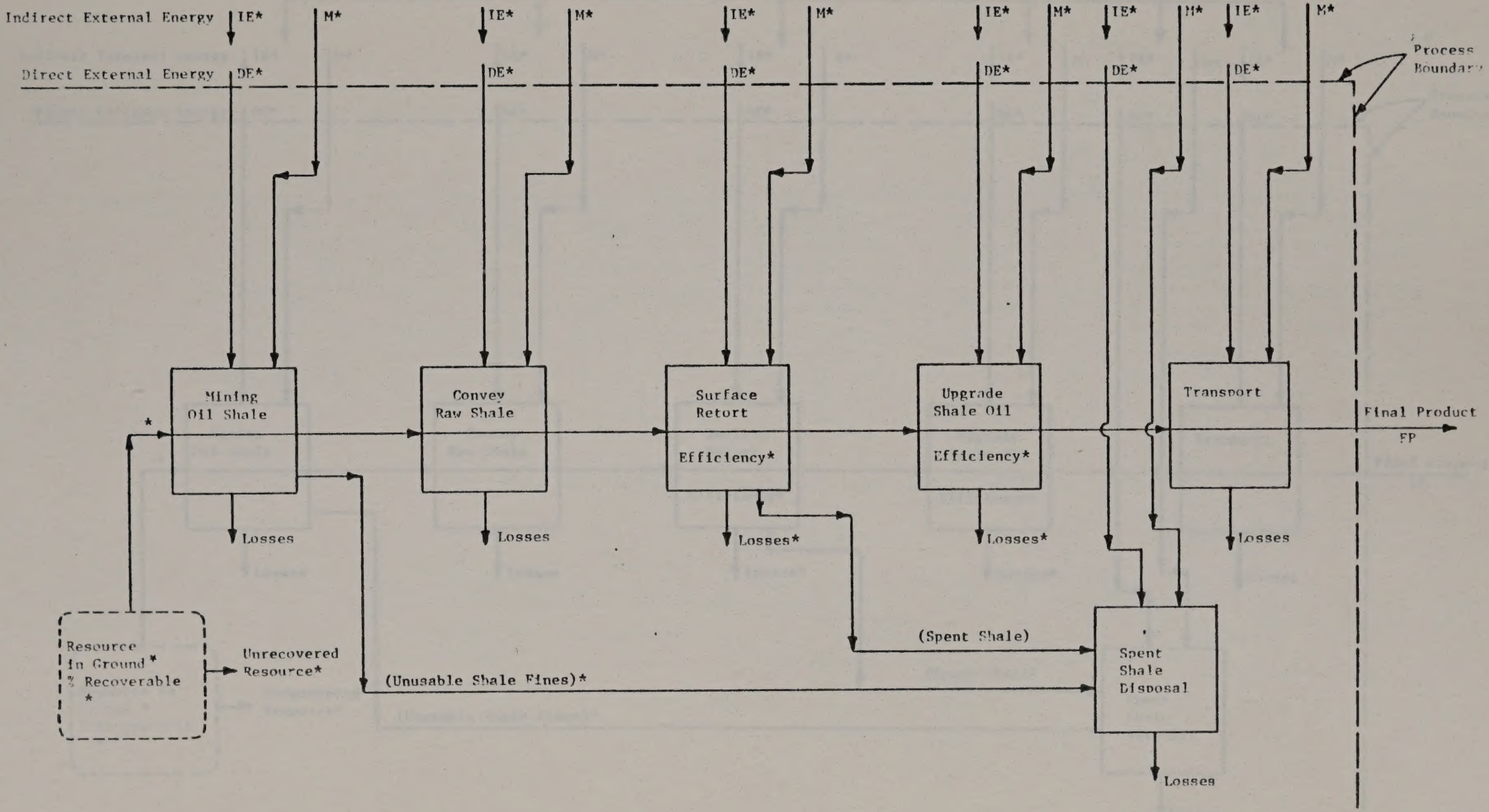


FIGURE 3.1d

General Method Step 3.2.1: Define Issues, Study Limits, Trajectory and Process Boundary

Example: Oil Shale Production, Surface Retorting

Case D: Trajectory: As shown — Data Required: Indicated by *

Study Limits: Included:
- Direct External Energy
- Recovered Resources in Ground
- Indirect External Energy
- Unrecovered Resources in Ground of Principal Energy
- Materials Energy

Excluded: Infrastructure Energy

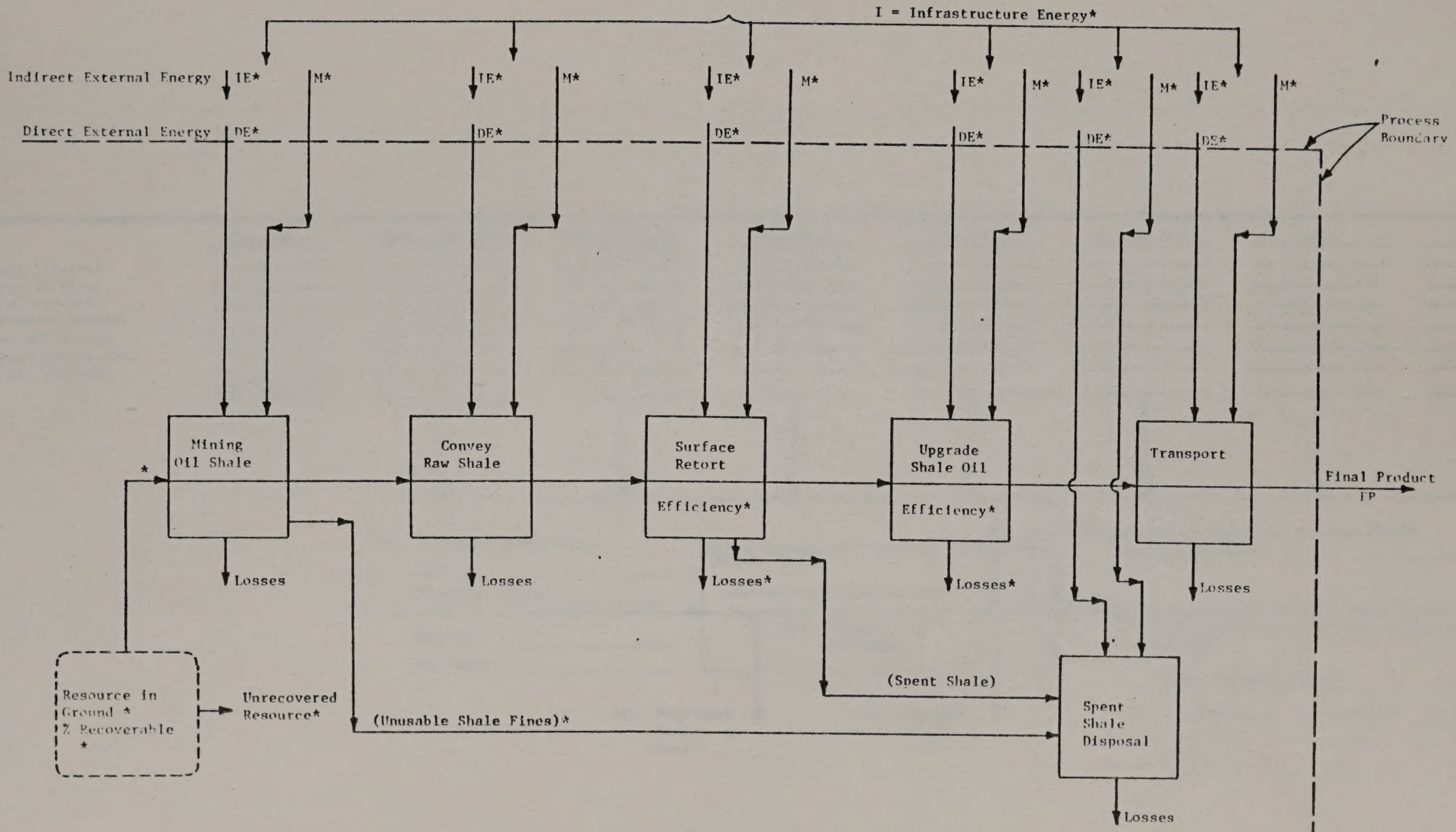


FIGURE 3.1e

General Method Step 3.2.1: Define Issues, Study Limits, Trajectory and Process Boundary

Example: Oil Shale Production, Surface Retorting

Case E: Trajectory: As shown — Data Required: Indicated by *

Study Limits: Included:
Direct External Energy
Recovered Resources in Ground
Indirect External Energy
Unrecovered Resources in Ground of Principal Energy
Materials Energy
Infrastructure Energy

Excluded: Nothing

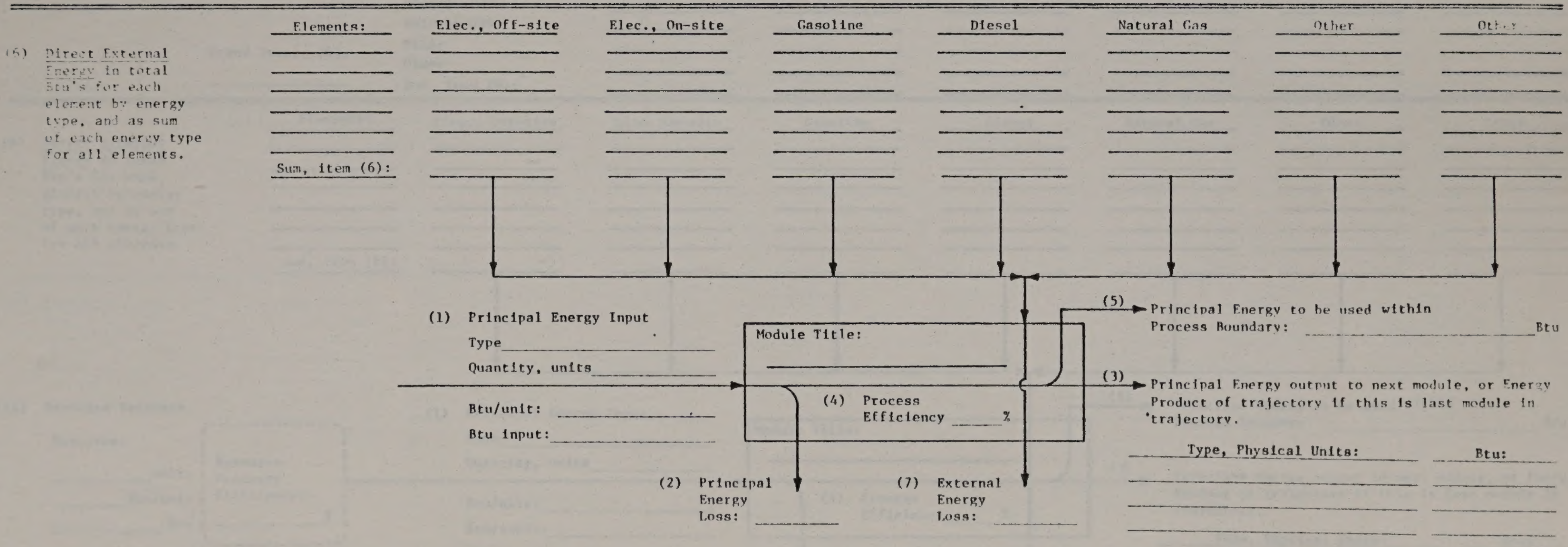

Elements:
Elec., Off-site
Elec., On-site
Gasoline
Diesel
Natural Gas
Other
Other
(6) Direct External Energy in total Btu's for each element by energy type, and as sum of each energy type for all elements.
Sum, item (6):
(1) Principal Energy Input
Type
Quantity, units
Btu/unit:
Btu input:
Module Title:
(4) Process Efficiency %
(2) Principal Energy Loss:
(7) External Energy Loss:
(5) Principal Energy to be used within Process Boundary: Btu
(3) Principal Energy output to next module, or Energy Product of trajectory if this is last module in trajectory.
Type, Physical Units:
Btu:

FIGURE 3.2a
General Method Step 3.2.2: Describe Modules with Elements, Inputs and Outputs
Case A: Direct External Energy and Principal Energy Input Included;
Indirect External Energy, Materials and Unrecovered Resources Excluded

(8) Total External Energy as Resources in Ground:

Direct Energy type:

	Crude Oil	Natural Gas	Coal	Hydropower	Nuclear	Other Energy
Electric, Off-site						
Electric, On-site						
Gasoline						
Diesel						
Natural Gas						
Other						
Other						
Sum, item (8):						

Grand Total, (8): ______________

(6) Direct External Energy in total Btu's for each element by energy type, and as sum of each energy type for all elements.

Elements:	Elec., Off-site	Elec., On-site	Gasoline	Diesel	Natural Gas	Other	Other
Sum, item (6):							

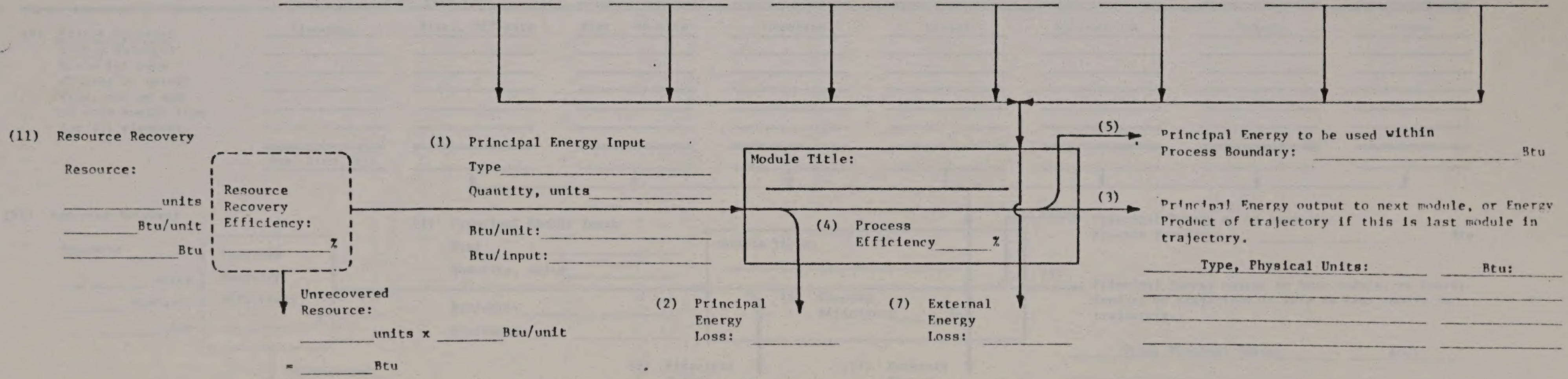

(11) Resource Recovery
Resource:
________units
________Btu/unit
________Btu
Resource Recovery Efficiency:
________%
Unrecovered Resource:
________units x ________Btu/unit
= ________Btu
(1) Principal Energy Input
Type________
Quantity, units________
Btu/unit:________
Btu/input:________
Module Title:
____
(4) Process Efficiency________%
(2) Principal Energy Loss: ________
(7) External Energy Loss: ________
(5)
Principal Energy to be used within Process Boundary: ________Btu
(3)
Principal Energy output to next module, or Energy Product of trajectory if this is last module in trajectory.
Type, Physical Units:
Btu:

FIGURE 3.2b

General Method Step 3.2.2: Describe Modules with Elements, Inputs and Outputs

Case B: Direct External Energy, Principal Energy Input, Indirect External Energy and Unrecovered Resource for Resource Extraction Module Included; Materials Energy Excluded

(10) Grand Total, External Energy Inputs (8)+(9):	Crude Oil	Natural Gas	Coal	Hydropower	Nuclear	Other Energy

(9) Energy in Materials, by type of energy, as resources in ground.

Material	Quantity, Units	Crude Oil	Natural Gas	Coal	Hydropower	Nuclear	Other Energy
	Sum, item (9):						

Grand Total, (9): ____________

(8) Total External Energy as Resources in Ground:	Crude Oil	Natural Gas	Coal	Hydropower	Nuclear	Other Energy
Direct Energy type: Electric, Off-site						
Electric, On-site						
Gasoline						
Diesel						
Natural Gas						
Other						
Other						
Sum, item (8):						

Grand Total, (8): ____________

(6) Direct External Energy in total Btu's for each element by energy type, and as sum of each energy type for all elements.

Elements:	Elec., Off-site	Elec., On-site	Gasoline	Diesel	Natural Gas	Other	Other
Sum, item (6):							

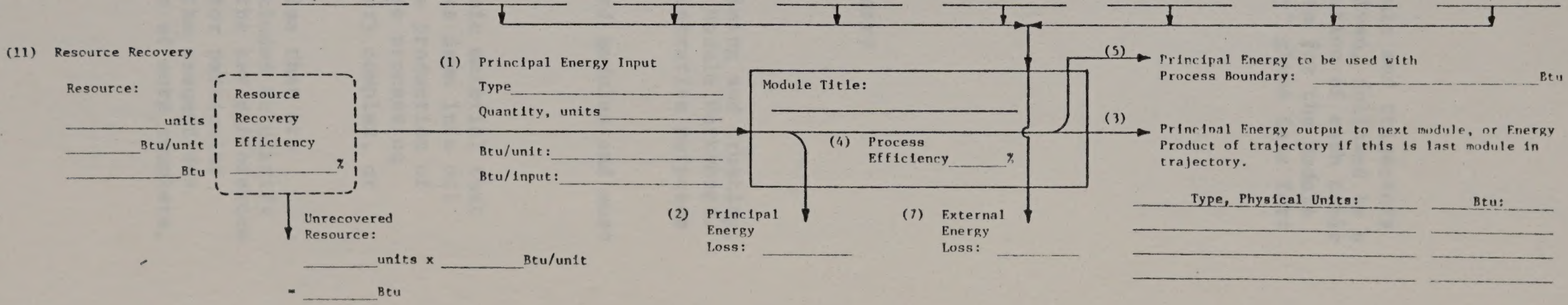

(11) Resource Recovery
Resource:
________ units
________ Btu/unit
________ Btu
Resource Recovery Efficiency ________ %
Unrecovered Resource:
________ units x ________ Btu/unit
= ________ Btu
(1) Principal Energy Input
Type ________
Quantity, units ________
Btu/unit: ________
Btu/input: ________
Module Title:
(4) Process Efficiency ______ %
(2) Principal Energy Loss: ________
(7) External Energy Loss: ________
(5) Principal Energy to be used with Process Boundary: ________ Btu
(3) Principal Energy output to next module, or Energy Product of trajectory if this is last module in trajectory.
Type, Physical Units:
Btu:

FIGURE 3.2c

Case C: General Method Step 3.2.2: Describe Modules with Elements, Inputs and Outputs
Direct External Energy, Principal Energy Input, Indirect External Energy, Unrecovered Resource for Resource Extraction Module, and Materials Energy Included

4. OIL SHALE ENERGY SYSTEMS:

DESCRIPTIONS AND MODULE DATA

Sections 4 and 6 contain the data for use in quantifying module and trajectory net energy. A brief description of each module process is given, followed by a table with assumptions, data and data sources. The final section of each table is a "Module Energy Summary", which lists information and data for the Module Worksheets. Refer to Figure 3.2c; the "Module Energy Summary" gives data for:

Item (1) Principal Energy Input
Type:
Quantity units:
Btu/unit:
Btu/input:

Item (2) Principal Energy Loss

Item (3) Principal Energy Output
Type: (can be several types)
Quantity units: (for each type)

Item (4) Process Efficiency

Item (5) Principal Energy to be used with Process Boundary

Item (11) Resource Recovery Efficiency:
(per cent)(where appropriate)

The discussion of the first module, Surface Oil Shale Mining and Crushing, 4.1.1.1, has a figure which shows how this data relates to a Module Worksheet. This is Figure 4.1. It is shown for only one module for illustrative purposes and is not repeated for any other modules.

As will be seen in Section 5, these data are for standard modules and must be scaled up to the size of the actual operation.

4.1 SHALE OIL PRODUCTION TECHNIQUES

Oil shale is a rock that contains kerogen, a solid organic material that cannot be extracted with conventional solvents but that breaks down into oil and combustible gas when heated to about 900°F. However, the production of usable fuels from oil shale requires that a number of discrete processing steps, or modules, be incorporated into a complete oil recovery complex, or trajectory.

The following sections present descriptions of the modules that are required to produce shale oil. Examples and diagrams are included to clarify the descriptions and to allow the handbook user to identify the key differences between alternative courses of action that may be available for particular modules. Energy and materials consumption data, as well as the assumptions that underlie those data, are included for use in the absence of more complete,

	Crude Oil	Natural Gas	Coal	Hydropower	Nuclear	Other Energy
(10) Grand Total, External Energy Inputs (8)+(9):						

(9) Energy in Materials, by type of energy, as resources in ground.

	Material	Quantity, Units	Crude Oil	Natural Gas	Coal	Hydropower	Nuclear	Other Energy
mining	Steel-mat'l handling	88.3 lbs/1087 tons						
	Rubber	39.0 " " "						
	Copper	0.3 " " "						
	Explosives	1,076 " " "						
crushing	Steel-mat'l handling	39.8 lbs/1000 tons						
	Concrete	0.068 tons/1000 tons						
		Sum, item (9):						

Grand Total, (9):

(8) Total External Energy as Resources in Ground:

Direct Energy type:	Crude Oil	Natural Gas	Coal	Hydropower	Nuclear	Other Energy
Electric, Off-site						
Electric, On-site						
Gasoline						
Diesel						
Natural Gas						
Other						
Other						
Sum, item (8):						

Grand Total, (8):

(6) Direct External Energy in total Btu's for each element by energy type, and as sum of each energy type for all elements.

Elements:	Elec., Off-site	Elec., On-site	Gasoline	Diesel	Natural Gas	Other	Other
Mining	2450 kwh/1087 tons	(see off-site-optional)	3.4 gal/1087 tons	225 gal/1087 tons	–	lub. oil 26.6 gal/1087 tons	
Crushing	831 kwh/1000 tons	" " " "	0	0	–	0	
Sum, item (6):							

(11) Resource Recovery

Resource:
1,279 tons/day ~~units~~
4.68×10^6 Btu/~~unit~~ ton
5.986×10^9 Btu

Resource Recovery Efficiency 85.0 %

Unrecovered Resource:
192 tons/day units × 4.68×10^6 Btu/~~unit~~ ton
= 899×10^6 Btu

(1) Principal Energy Input
Type 26 gal/ton oil shale
Quantity, units 1087 tons/day
Btu/unit: 4.68×10^6 Btu/ton
Btu input: 5.087×10^9 Btu/day

Module Title: Surface oil shale mining

(4) Process Efficiency 92 %

(2) Principal Energy Loss: 407×10^6 Btu/day

(7) External Energy Loss:

(5) Principal Energy to be used with Process Boundary: None Btu

(3) Principal Energy output to next module, or Energy Product of trajectory if this is last module in trajectory.

Type, Physical Units:	Btu:
Crushed oil shale, 1000 tons/day	4.680×10^9 Btu/day

FIGURE 4.1

Module Data for Standard Module: Surface Oil Shale Mining

Scaling Factor for Standard Module N.A. Standard Module 4.4.1.1

project-specific data. In general, these data have been taken from the literature and are based on preliminary engineering design rather than actual operating experience.

The module descriptions that follow are presented sequentially from the beginning of a trajectory to the end. This approach should make it easier for the handbook user to perform the net energy analysis on a logical, step-by-step basis.

4.1.1 Oil Shale Mining

A number of methods are available for mining an oil shale deposit in conjunction with the recovery of oil from the shale. In general, these methods can be divided into three major categories: surface mining, underground mining, and preparation of a modified in-situ (MIS) retort. The following sections describe each of these options.

4.1.1.1 Surface Oil Shale Mining

The two principal types of surface mining - open pit and strip - have both been widely used to develop coal seams and deposits of many other minerals. Surface mining is economically attractive for large, low-grade or deposits because it permits high recovery of the resource and allows sufficient space for very large and efficient mining equipment. An open pit mine could recover about 90% of the oil shale in a very thick deposit compared to less than 60% for an underground mine.

Open pit mining is conceptually simple, and its technical aspects are well understood. In the first step, overburden is drilled and blasted loose over a large area above the oil shale zone. The overburden is carried by trucks or conveyors to an offsite disposal area. When enough overburden is removed to expose the shale beds, the shale itself is drilled and blasted, and is hauled from the pit for processing in surface retorts. As mining proceeds, a huge hole is formed, extending from the top of the overburden to deep into the oil shale deposit. The walls of the pit are under pressure from the overburden, and must be angled outwards to transmit the pressure without collapsing.

Surface mining of most oil shale deposits is made difficult by the great thickness of overburden that covers them. In the center of the Piceance Creek Basin, for example, the 2,000-ft-thick oil shale zones are buried under about 1,000 ft of inert rock and very lean oil shale. This does not necessarily preclude surface mining, because the deposits are generally characterized by a favorable stripping ratio - the ratio of overburden thickness to ore body thickness. The thick beds in the center of the Piceance Creek Basin have a stripping ratio of 1:2.

However, one should not gauge the feasibility of open pit mining by stripping ratio alone. Removal of 1,000 ft of overburden would require a very large tract to contain the resulting pit. In addition, the large "front-end" investment required to remove overburden many years in advance of retorting would probably make open pit mining of deep deposits uneconomical.

Once the shale is mined, it must be crushed to the proper size consist before it can be fed to a surface retort. Oil shale generally undergoes two or three stages of crushing before being transported to the retort. Two stages have been assumed for the purposes of this handbook.

Primary crushing is the first size reduction undertaken in preparing oil shale for processing. The purpose of primary crushing is to reduce the oil shale to a size that is transportable and suitable for secondary crushing. Various machines are used, all of which operate by applying impact, compressive, or shear forces to the oil shale.

Crusher characteristics that must be considered include:

- Maximum feed size that can be handled
- Head-room needed
- Mobility
- Product characteristics
- Capacity
- Feed rate and method
- Capital, operating, and maintenance costs per ton of product
- Power required per ton of product
- Dust and noise production

The crushing behavior of oil shale must also be taken into account. Oil shale is a tough, laminated rock that requires more crushing work than its mineralogy would suggest.

Secondary crushing is the size reduction step that follows primary crushing. Secondary crushers work on the same principles and are similar in essential features to primary crushers. However, since some of the product from the primary crusher is already small enough to be fed directly to the retort, the production demands on the secondary crusher are less than or the primary crusher.

Secondary crusher characteristics that must be considered include:

- Top feed size to crusher
- Product size
- Capacity
- Costs per ton of product
- Acceptable level of fines in product

Crushers suitable for oil shale come in all sizes, are of standard manufacture, and can be obtained quite easily.

Module Elements and Data

The surface mining module consists of two elements: (1) mining and (2) crushing. Table 4.1 describes each of these elements.

TABLE 4.1

Module: Surface Oil Shale Mining

Element 1: Mining

(a) Equipment, facilities

Power shovels
Bulldozers
Dump trucks
Tank trucks
Drills
Graders
Loaders
Haulers
Scrapers
Pumps
Cranes
Miscellaneous light duty vehicles

(b) Assumptions

(1) Retort output at 90% recovery is 50,000 barrels per day, 365 days per year.
(2) Mine operation is 355 days per year.
(3) Shale seam thickness is 100 ft with 100 ft of overburden. Stripping ratio is 1:1.
(4) Life of mine is 20 years.

(c) Guidelines on data

(1) Data must be multiplied by thousands of tons of oil shale mined.

(d) Data

(1) Direct energy and materials for mining (output) 26 gal/ton shale.

Diesel fuel	225 gallons/1087 tons	Ref. No. 4
Gasoline	3.4 gallons/1087 tons	Ref. No. 4
Lubricating oil	26.6 gallons/1087 tons	Ref. No. 4
Electricity	2,450 kwh/1087 tons	Ref. No. 4
Steel	88.3 lbs/1087 tons	Ref. No. 4
Rubber	39.0 lbs/1087 tons	Ref. No. 4
Copper	0.30 lbs/1087 tons	Ref. No. 4
Explosives	1,036 lbs/1087 tons	Ref. No. 4

TABLE 4.1

Continued

(2) Direct energy and materials for mining (output) 34 gal/ton shale.

Diesel fuel	217 gallons/1087 tons	Ref. No. 4
Gasoline	3.7 gallons/1087 tons	Ref. No. 4
Lubricating oil	25.7 gallons/1087 tons	Ref. No. 4
Electricity	2,403 kwh/1087 tons	Ref. No. 4
Steel	86.9 lbs/1087 tons	Ref. No. 4
Rubber	37.7 lbs/1087 tons	Ref. No. 4
Copper	0.27 lbs/1087 tons	Ref. No. 4
Explosives	1,065 lbs/1087 tons	Ref. No. 4

(3) Efficiency and Losses

- o Recovery of the in-place oil shale resource by mining is assumed to be 85%.
- o All fuel and power consumption for the mining element are considered losses from the module.

(e) Data sources

(1) Office of Technology Assessment, 1980, An assessment of oil shale technologies: Washington D.C., Office of Technology Assessment, 517 p.
(2) TRW Energy Systems Group, 1979, Oil shale data book: McLean, Virginia, TRW Energy System Group, 439 p.
(3) Melcher, A.G., and others, 1976, Net energy analysis--an energy balance study of fossil fuel resources: Golden, Colorado, The Colorado Energy Research Institute, 218 p.
(4) Private communications with mining and engineering companies.
(5) Baughman, G.L., 1978, Synthetic fuels data handbook: Denver, Colorado, Cameron Engineers, Inc., 438 p.

TABLE 4.1

Continued

Element 2: Crushing

(a) Equipment, facilities

Primary crushers (gyratory, jaw, impactor, or toothed roll)
Secondary crushers (impact, jaw, toothed roll, cone, or hammer mills)
Conveyors

(b) Assumptions

(1) Approximately 8% of the crusher feed is lost as fines.
(2) Operation is 355 days per year.

(c) Guidelines on data

(1) Data must be multiplied by thousands of tons of oil shale mined.

(d) Data

(1) Direct energy and materials for crushing (output) 26 gal/ton shale.

Electricity	831 kwh/1000 tons	Ref. No. 4
Steel	39.8 lbs/1000 tons	Ref. No. 4
Concrete	0.086 tons/1000 tons	Ref. No. 4

(2) Direct energy and materials for crushing (output) 34 gal/ton shale.

Electricity	727 kwh/1000 tons	Ref. No. 4
Steel	40.5 lbs/1000 tons	Ref. No. 4
Concrete	0.017 tons/1000 tons	Ref. No. 4

(3) Efficiency and Losses

o Approximately 8% of the crusher feed is lost as fines.
o All power consumption for crushing is considered a loss from the module.

(e) Data sources

(1) Office of Technology Assessment, 1980, An assessment of oil shale technologies: Washington D.C., Office of Technology Assessment, 517 p.
(2) TRW Energy Systems Group, 1979, Oil shale data book: McLean, Virginia, TRW Energy System Group, 439 p.
(3) Melcher, A.G., and others, 1976, Net energy analysis--an energy balance study of fossil fuel resources: Golden, Colorado, The Colorado Energy Research Institute, 218 p.
(4) Private communications with mining and engineering companies.
(5) Baughman, G.L., 1978, Synthetic fuels data handbook: Denver, Colorado, Cameron Engineers, Inc., 438 p.

TABLE 4.1

Continued

Module Energy Summary: 26 gal/ton

(1) Principal Energy Input
Type: 26 gal/ton oil shale
Quantity, units: 1087 tons/day
Btu/unit: 2340 Btu/lb = 4.68×10^6 Btu/ton
Btu input: 5.087×10^9 Btu/day
(2) Principal Energy Loss
407.2×10^6 Btu/day
(3) Principal Energy Output
Type: Crushed oil shale
Quantity: 1000 tons/day = 4.680×10^9 Btu/day
(4) Process Efficiency
Mining = 100%
Crushing = 92%
Overall = 92%
(5) Principal Energy to be used within Process Boundary
None
(11) Resource Recovery
Efficency = 85%; "output" for mining recovery = 1087 tons/day;
resource required = 1,279 tons/day

Module Energy Summary: 34 gal/ton

(1) Principal Energy Input
Type: 34 gal/ton oil shale
Quantity, units: 1087 tons/day
Btu/unit: 3100 Btu/lb = 6.20×10^6 Btu/ton
Btu input: 6.739×10^9 Btu/day
(2) Principal Energy Loss
539×10^6 Btu/day
(3) Principal Energy Output
Type: Crushed oil shale
Quantity: 1000 tons/day = 6.20×10^9 Btu/day
(4) Process Efficiency
Mining = 100%
Crushing = 92%
Overall = 92%
(5) Principal Energy to be used within Process Boundary
None
(11) Resource Recovery
Efficency = 85%; "output" for mining recovery = 1087 tons/day;
resource required = 1,279 tons/day

4.1.1.2 Underground Oil Shale Mining

Many underground mining techniques have been proposed for the development of oil shale deposits in conjunction with surface retorting of the shale. Some of these are room-and-pillar, longwall, sub-level stoping, and block caving. However, to date only conventional room-and-pillar mining has been tested at any significant scale. In addition, room-and-pillar mining has been selected for use by several major oil shale developers. For these reasons, room and pillar mining is the method of choice to be discussed in this handbook.

In room-and-pillar mining, some shale is removed to form large rooms and some is left in place, as pillars, to support the mine roof. Work by the Bureau of Mines has shown that for safe mining conditions, the rooms should be 60 ft wide with pillars that are 60 ft on a side. In addition, the strength of the rock in oil shale seams that are rich enough for commercial development usually results in the mine roof being 60 ft high.

The mining of oil shale to form rooms of the size indicated above can be done in a single pass or in two passes. In the single pass system shown in Figure 4.2, the entire ore thickness is taken in one pass. This system requires fewer blasting cycles, thus creating less pillar disturbance, and results in fewer equipment moves for a given level of production. However, single-pass room-and-pillar mining would require the use of very large equipment, some of which is not readily available.

The benching system of room-and-pillar mining, shown in Figure 4.3, is used to mine the shale from two or more levels, or benches. This method has been proven in prototype oil shale operations and does not require the use of extremely large equipment. As shown in Figure 4.3, mining is conducted on two benches. The upper bench is mined first by drilling blastholes into the walls of a production room and breaking the shale loose with explosives. The broken shale is transported to the underground primary crushers where initial size reduction is performed. Secondary crushing to the size range required by the retorts can be done underground or the shale can be transported to the surface for secondary crushing.

After the broken shale has been removed from the production room, the walls and the roof of the room are "scaled" to remove shale that was loosened by the blasting but did not fall. Holes are then drilled into the mine roof and roof bolts are inserted to assure its integrity. US Bureau of Mines studies indicate that roof bolts must be installed in the access passageways but not in areas that are actively being mined since these production rooms would be vacated long before there was any serious danger of roof falls.

The lower bench is mined next. The angle is similar except that the blastholes are drilled into the floor of the upper bench, and additional roof bolting is not needed.

The cycle of drilling, blasting, loading, scaling, and roof bolting is designed to produce large tonnages of oil shale for surface retorting. For example, the room-and-pillar mine of the Colony Development Operation is designed to produce 66,000 tons per day of oil shale to supply retorts producing 46,000 barrels per day of shale oil. However, recovery is relatively

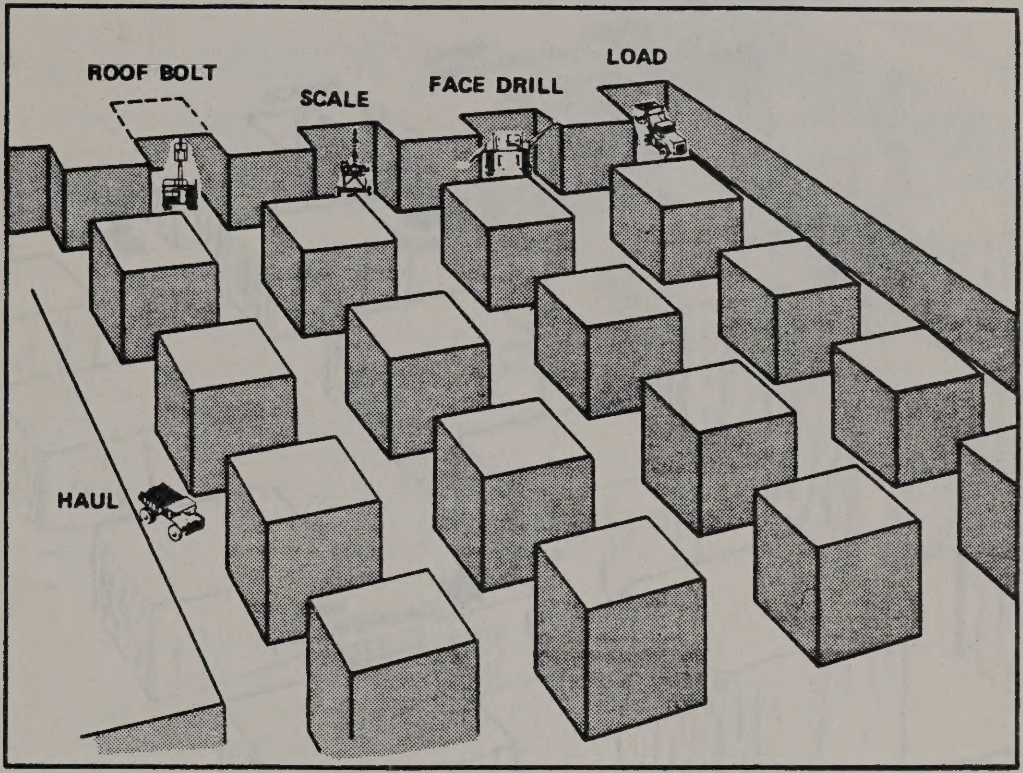


FIGURE 4.2

Single-Pass Room-and-Pillar Mining

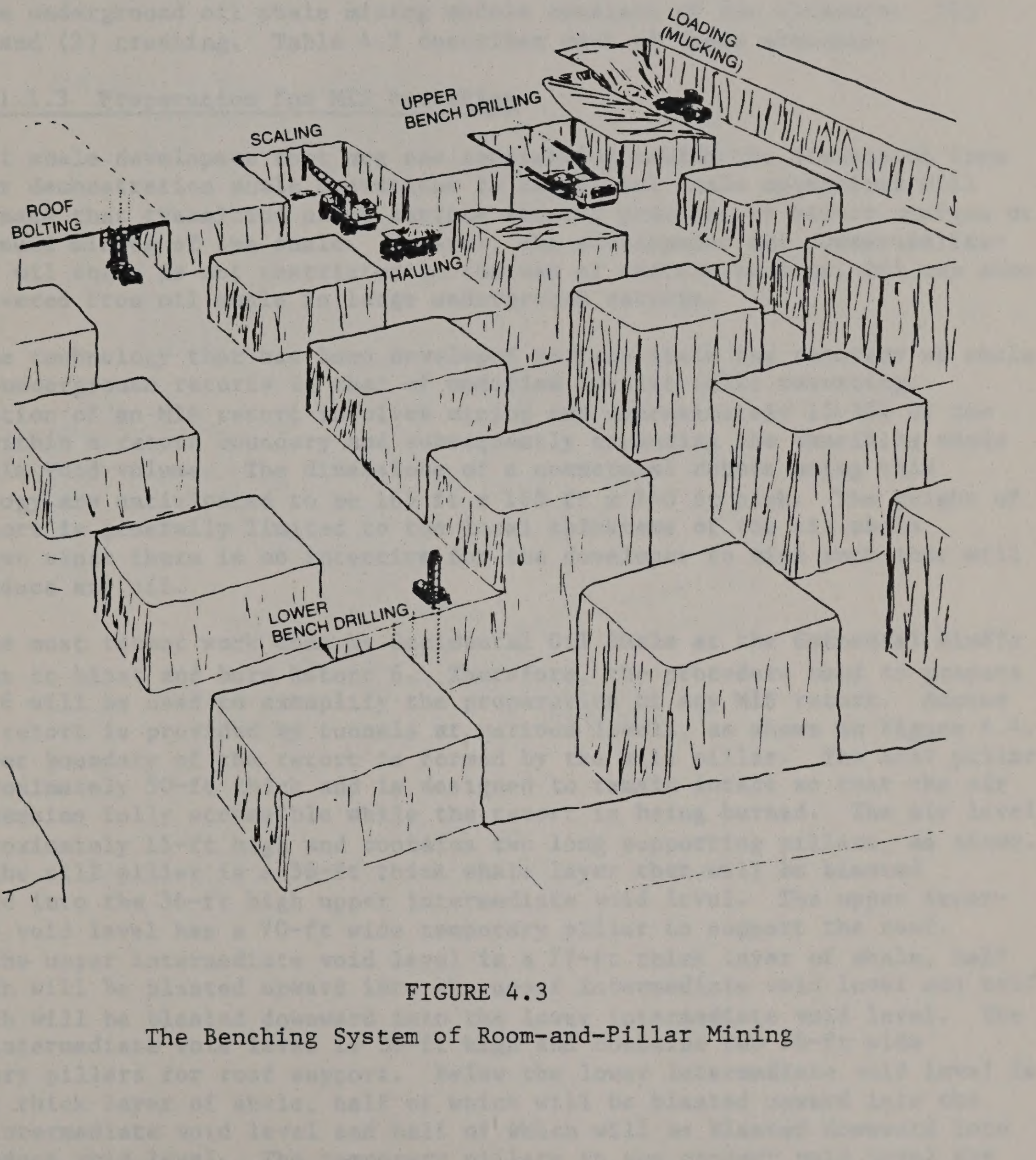


FIGURE 4.3

The Benching System of Room-and-Pillar Mining

low. About 60% of the shale in Colony's mining zone is to be removed for processing with 40% to remain in the support pillars.

Proper mine ventilation is of paramount importance in the operation of an undeground oil shale mine. Electric blowers must supply a steady stream of fresh air for miners to breath, for equipment to function, and to sweep away exhaust fumes and potentially explosive gases and dust that are produced during the mining operation.

Module Elements and Data

The underground oil shale mining module consists of two elements: (1) mining and (2) crushing. Table 4.2 describes each of these elements.

4.1.1.3 Preparation for MIS Retorting

Oil shale developers that are now considering making the transition from pilot or demonstration scale operations to commercial scale operations will likely make that transition using surface retorts preceded by either surface or underground mining of the shale. However, the development and commercialization of oil shale is not restricted to the use of surface retorts. Oil can also be recovered from oil shale in large underground retorts.

One technology that has been developed to facilitate the recovery of shale oil in underground retorts is that of modified in-situ (MIS) retorting. Preparation of an MIS retort involves mining out approximately 15-35% of the shale within a retort boundary and subsequently expanding the remaining shale into this void volume. The dimensions of a commercial retort using this technology are anticipated to be 165 ft x 165 ft x 240 ft high. The height of the retort is generally limited to the local thickness of the oil shale formation since there is no incentive for the developer to mine rock that will not produce any oil.

The most recent work done by Occidental Oil Shale at the Cathedral Bluffs site was to blast and burn Retort 6. Therefore, the procedure used to prepare Retort 6 will be used to exemplify the preparation of any MIS retort. Access to the retort is provided by tunnels at various levels, as shown in Figure 4.4. The upper boundary of the retort is formed by the sill pillar. The sill pillar is approximately 50-ft thick and is designed to remain intact so that the air level remains fully accessible while the retort is being burned. The air level is approximately 15-ft high and contains two long supporting pillars, as shown. Below the sill pillar is a 36-ft thick shale layer that will be blasted downward into the 36-ft high upper intermediate void level. The upper intermediate void level has a 70-ft wide temporary pillar to support the roof. Below the upper intermediate void level is a 77-ft thick layer of shale, half of which will be blasted upward into the upper intermediate void level and half of which will be blasted downward into the lower intermediate void level. The lower intermediate void level is 36-ft high and contains two 36-ft wide temporary pillars for roof support. Below the lower intermediate void level is a 66-ft thick layer of shale, half of which will be blasted upward into the lower intermediate void level and half of which will be blasted downward into the product void level. The temporary pillars in the product void level are 20-ft wide.

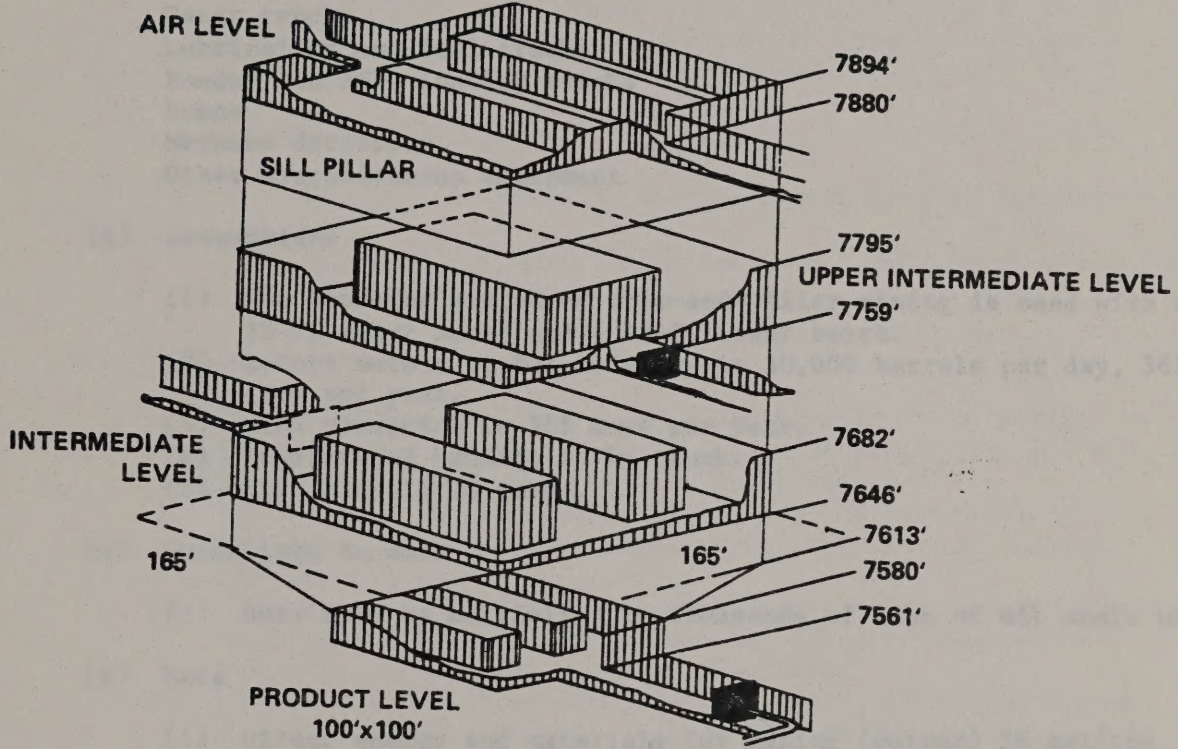


FIGURE 4.4
Isometric View of Retort 6, Modified In Situ Retort

TABLE 4.2

Module: Underground Oil Shale Mining

Element 1: Mining

(a) Equipment, facilities

Hydraulic drill jumbos
LHD machines
Rock bolt machines
Ventilation fans
Water trucks
Lubrication and fuel trucks
Powder and ANFO loading trucks
Pumps
Methane detectors
Other miscellaneous equipment

(b) Assumptions

(1) The benching system of room-and-pillar mining is used with a 35-ft upper bench and a 25-ft lower bench.
(2) Retort output at 90% recovery is 50,000 barrels per day, 365 days per year.
(3) Mine operation is 355 days per year.
(4) Underground haulage is by truck.
(5) Mine life is 20 years.

(c) Guidelines on data

(1) Data must be multiplied by thousands of tons of oil shale mined.

(d) Data

(1) Direct energy and materials for mining (output) 26 gal/ton shale.

Diesel fuel	326 gallons/1087 tons	Ref. No. 5
Lubricating oil	13.3 gallons/1087 tons	Ref. No. 5
Electricity	3,260 kwh/1087 tons	Ref. No. 5
Steel	211 lbs/1087 tons	Ref. No. 5
Rubber	77.3 lbs/1087 tons	Ref. No. 5
Copper	0.0987 lbs/1087 tons	Ref. No. 5
Concrete	0.0233 cu yd/1087 tons	Ref. No. 5
Explosives	366 lbs/1087 tons	Ref. No. 5

TABLE 4.2

Continued

(2) Direct energy and materials for mining (output) 34 gal/ton shale.

Diesel fuel	347 gallons/1087 tons	Ref. No. 5
Lubricating oil	13.9 gallons/1087 tons	Ref. No. 5
Electricity	3,053 kwh/1087 tons	Ref. No. 5
Steel	210 lbs/1087 tons	Ref. No. 5
Rubber	77.5 lbs/1087 tons	Ref. No. 5
Copper	0.1087 lbs/1087 tons	Ref. No. 5
Concrete	0.0287 cu yd/1087 tons	Ref. No. 5
Explosives	546 lbs/1087 tons	Ref. No. 5

(3) Efficiency and Losses

- o Recovery of oil shale in the mining seam is assumed to be 60%.
- o All fuel and power requirements for the mining element are considered losses from the module.

(e) Data sources

(1) Bechtel Petroleum, Inc., 1981, White river shale project--detailed development plan for oil shale tracts U-a and U-b: San Francisco, California, Bechtel Petroleum, Inc.

(2) Office of Technology Assessment, 1980, An assessment of oil shale technologies: Washington D.C., Office of Technology Assessment, 517 p.

(3) Sladek, T.A., 1975, Recent trends in oil shale--Part 2: Mining and shale oil extraction processes: Mineral Industries Bulletin, v. 18, no. 1, 20 p., January.

(4) East, J.H., Jr., and Gardner, E.D., 1964, Oil-shale mining, Rifle, Colorado, 1944-56: U.S. Bureau of Mines Bulletin 611, 163 p.

(5) Private communications with mining and engineering companies.

(6) Marshall, P.W., 1974, Colony Development Operation room-and-pillar oil shale mining: Golden, Colorado, Quarterly of the Colorado School of Mines, v. 69, no. 2, April.

(7) Hoskins, W.N., and Hutchins, J.S., 1975, A technical and economic study of candidate underground mining systems for deep, thick oil shale deposits--Phase I report: Denver, Colorado, Cameron Engineers, Inc., July.

TABLE 4.2

Element 2: Crushing

(a) Equipment, facilities

Portable impact crushers
Conveyors

(b) Assumptions

(1) Approximately 8% of the crusher feed is lost as fines.
(2) Operation is 355 days per year.

(c) Guidelines on data

(1) Data must be multiplied by thousands of tons of oil shale mined.

(d) Data

(1) Direct energy and materials for crushing (output) 26 gal/ton shale.

Electricity	652 kwh/1000 tons	Ref. No. 4
Steel	36.1 lbs/1000 tons	Ref. No. 4
Concrete	0.0055 cu yd/1000 tons	Ref. No. 4

(2) Direct energy and materials for crushing (output) 34 gal/ton shale.

Electricity	515 kwh/1000 tons	Ref. No. 4
Steel	36.5 lbs/1000 tons	Ref. No. 4
Concrete	0.0056 Cu yd/1000 tons	Ref. No. 4

(3) Efficiency and Losses

- Approximately 8% of the crusher feed is lost as fines.
- All power consumption for crushing is considered a loss from the module.

(e) Data sources

(1) Office of Technology Assessment, 1980, An assessment of oil shale technologies: Washington D.C., Office of Technology Assessment, 517 p.
(2) TRW Energy Systems Group, 1979, Oil shale data book: McLean, Virginia, TRW Energy System Group, 439 p.
(3) Melcher, A.G., and others, 1976, Net energy analysis--an energy balance study of fossil fuel resources: Golden, Colorado, The Colorado Energy Research Institute, 218 p.
(4) Private communications with mining and engineering companies.
(5) Baughman, G.L., 1978, Synthetic fuels data handbook: Denver, Colorado, Cameron Engineers, Inc., 438 p.

TABLE 4.2

Continued

Module Energy Summary: 26 gal/ton

(1) Principal Energy Input
Type: 26 gal/ton oil shale
Quantity, units: 1087 tons/day
Btu/unit: 2340 Btu/lb = 4.68×10^6 Btu/ton
Btu input: 5.087×10^9 Btu/day

(2) Principal Energy Loss
407.2×10^6 Btu/day

(3) Principal Energy Output
Type: Crushed oil shale
Quantity: 1000 tons/day = 4.68×10^9 Btu/day

(4) Process Efficiency
Mining = 100%
Crushing = 92%
Overall = 92%

(5) Principal Energy to be used within Process Boundary
None

(11) Resource Recovery
Efficiency = 60%; "output" for mining recovery = 1087 ton/day; resource required = 1,812 tons/day

Module Energy Summary: 34 gal/ton

(1) Principal Energy Input
Type: 34 gal/ton oil shale
Quantity, units: 1087 tons/day
Btu/unit: 3100 Btu/lb = 6.20×10^6 Btu/ton
Btu input = 7.739×10^9 Btu/day

(2) Principal Energy Loss
5393×10^6 Btu/day

(3) Principal Energy Output
Type: Crushed oil shale
Quantity: 1000 tons/day = 6.20×10^9 Btu/day

(4) Process Efficiency
Mining = 100%
Crushing = 92%
Overall = 92%

(5) Principal Energy to be used within Process Boundary
None

(11) Resource Recovery
Efficiency = 60%; "output" for mining recovery = 1087 ton/day; resource required = 1,812 tons/day

The void levels are produced by using the same equipment and techniques that were described in the previous section for room-and-pillar mining of oil shale. However, energy consumption for this portion of the retort preparation process is considerably reduced because of the reduced tonnages of rock that must be mined. After the void levels are completed, the support pillars and interlying shale layers are sequentially blasted to produce a uniformly rubbled mass with a void volume equal to the void volume before blasting.

In order to produce 50,000 barrels per day of crude shale oil per day from shale averaging 20 gallons per ton, a retort will have to be developed each 2-1/2 days and roughly 80 retorts will have to be burning simultaneously. These figures assume that oil recovery from the shale will be approximately 60% of Fischer array. Resource utilization estimates vary according to the assumptions that are made. However, if it is assumed that the retorts are spaced so that the shale in the walls between adjacent retorts can be retorted as well as the rubble within the retort walls, then roughly 70% of the shale contained on the site can be utilized.

The overall trajectory including this module will also have to have a surface-retorting module involved to handle the mined-out shale, unless this is to be unretorted for any reason. Hence, the trajectory will split the Principal Energy flows.

Module Elements and Data

The module for preparation of MIS retorts is presented here as a single element since data are available on that basis. Table 4.3 describes the module.

TABLE 4.3

Module: Preparation for MIS Retorting

(a) Equipment, facilities

Conveyors
Tunnel boring machines
Drills
Powder rigs
Compressors
Front end loaders
Haulage trucks
Mini-full facers
Crushers/feeders
Service trucks
Road graders
Fans
Personnel carriers
Pumps

(b) Assumptions

(1) The total production of oil from the site is 50,000 barrels per days.
(2) Operating life is 17.73 years.
(3) Shale grade is 20 gallons per ton.
(4) Operation is 24 hours per day, 365 days per year.

(c) Guidelines on data

(1) The data apply to an oil shale operation producing 50,000 barrel per day of crude shale oil.
(2) The data may be adjusted to other production rates by simple ratio.
(3) The data represent annual energy consumption.

(d) Data

(1) Direct energy and materials for preparing MIS retorts for a 50,000 barrel per day operation.

Electricity	507.44×10^6 kwh/yr	Ref. No. 2
Diesel fuel	16.93×10^6 gal/yr	Ref. No. 2
Explosives	22,620 tons/yr	Ref. No. 3
Equipment & Materials	1.09×10^{12} Btu/yr	Ref. No. 3

(2) Efficiency and Losses

- Recovery of the in-place oil shale resource is estimated at 70%, due to allowable retort spacing. (For in-retort kerogen recovery during burn, see subsequent module.)
- All fuel and power consumption during retort preparation is considered a loss from the module.

TABLE 4.3

Continued

(e) Data sources

(1) Ricketts, T.E., 1980, Occidental's retort 6 rubblizing and rock fragmentation program: Golden, Colorado, Thirteenth Oil Shale Symposium Proceeding, Colorado School of Mines, August.
(2) Marland, G., 1977, Net energy analysis of in situ oil shale processing: Oak Ridge Associated Universities, February.
(3) Ash, J.L., Stone, R.B., Craig, W.E., and Engler, M.R., 1976, Technical and economic study of the modified in situ process for oil shale: Tulsa, Oklahoma, Fenix & Scisson, Inc., 344 p.
(4) Cha, C.Y., and Garrett, D.E. Energy efficiency of the Garrett in-situ oil shale process.

Module Energy Summary:

(1) Principal Energy Input
Type: 20 gal/ton oil shale
Quantity, units: 250,000 tons/day
Btu/unit: 1760 Btu/lb = 3.52 x 10^6 Btu/ton
Btu input: 880.0 x 10^9 Btu/day

(2) Principal Energy Loss
None

(3) Principal Energy Output
(a) Type: Mined-out shale for surface retorting
Quantity: 75,000 tons/day = 264.0 x 10^9 Btu/day

(b) Type: Shale ready for retort burn
Quantity: 175,000 tons/day = 616.0 x 10^9 Btu/day

(4) Process Efficiency
Overall = 100%

(5) Principal Energy to be used within Process Boundary
None

(11) Resource Recovery
Efficiency = 70

4.1.2 Transportation of Raw Shale

In general, after the oil shale has been mined by either surface or underground techniques, it still must be transported by some means to the raw shale stockpile from which the retorts are fed. Two methods that can be used to transport the raw shale are conveyor and truck haulage.

4.1.2.1 Conveyor

Because of the likelihood of foul weather on Colorado's western slope, the use of covered conveyors is anticipated by most developers, when conveyors are used at all. Conveyors are very convenient for the operation because, once set in motion, they don't require any further operator attention. The primary form of energy consumption is electricity. Data are given for a typical mine-mouth retorting operation in Table 4.4, and for general conveying. For the latter, if the analyst is confronted with a process where the retort is some miles away from the mine, the module data of the table will be applicable.

In some cases, it is necessary to transport the raw shale downhill by conveyor for a considerable distance. If the slope of the conveyors and the tonnage being transported by that conveyor are properly matched, it is possible to turn the conveyor system from an electricity consumer to an electricity generator, or dynamic brake. While specific data for this type of a system could not be obtained for this handbook, it is certainly an option that should be examined on a site-by-site basis.

Module Elements and Data

The conveyor module consists of only one element. Data and assumptions for this module are presented in Table 4.4a.

4.1.2.2 Truck

Transporting by truck involves no more than loading the shale onto the truck, hauling it the necessary distance, and the dumping it onto the stockpile. Truck haulage is compatible with either surface or underground mining and most of the energy that is consumed is in the form of diesel fuel for the trucks.

TABLE 4.4b

Module: Transportation of Raw Shale - Conveyor

(a) Equipment, facilities

Conveyors and belts

(b) Assumptions

(1) 24 hour per day operation.
(2) Relatively flat terrain.

(c) Guidelines on data

(1) The data are presented for each 1000 tons of raw shale transported and must be multiplied by the appropriate production rate.

(d) Data

(1) Direct energy and materials for conveying 1000 tons of raw oil shale: Mine-mouth retorting

Electricity	129 kwh/1000 tons	Ref. No. 1
Steel	5.0 lbs/1000 tons	Ref. No. 1
Rubber	4.9 lbs/1000 tons	Ref. No. 1

Direct energy and materials for conveying 1000 tons of raw oil shale: from mine-mouth to retort, for 1000 tons-miles/year

Electricity	5300 kwh/1000 tons mi/yr	Ref. No. 1
Steel	0.11 lbs/1000 tons mi/yr	Ref. No. 1
Rubber	.052 lbs/1000 tons mi/yr	Ref. No. 1

(2) Efficiency and Losses

- o No physical shale losses are anticipated for this option.
- o All power consumption is considered a loss from the module.

(e) Data sources

(1) Private communications with mining and engineering companies

Module Energy Summary:

(1) Principal Energy Input
Type: Oil shale, any grade, crushed
Quantity, units: Btu input = Btu output
Btu/unit: Consistent with shale grade
Btu input: Consistent with shale grade and quantity

TABLE 4.4a

Continued

(2) Principal Energy Loss
None

(3) Principal Energy Output
Type: Crushed oil shale
Quantity: Btu output = Btu input into retort; calculate tonnage as appropriate

(4) Process Efficiency
100%

(5) Principal Energy to be used within Process Boundary
None

TABLE 4.4b

Module: Transportation of Raw Shale - Truck

(a) Equipment, facilities

150 ton capacity trucks

(b) Assumptions

(1) Require 66,000 STPD of raw shale for retort feed.
(2) Haulage distance is 1 mile, round trip.
(3) Truck fuel conumption is 1 gallon per mile.
(4) Maximum payload is 150 tons per truck per trip.
(5) Average speed is 15 mph (including loading and dumping.
(6) Vehicle weight = 137,000 lbs (113,000 lbs of steel, 24,000 lbs of rubber)
(7) Operation is 24 hours per day.

(c) Guidelines on data

(1) The data have been developed on the basis of 66,000 tons of raw shale hauled per day. Data can be scaled up or down by ratio on the basis of production.

TABLE 4.4b

Continued

(d) Data

(1) Direct energy and materials for truck hauling of 66,000 tons of raw shale per day.

Diesel fuel	440 gallons/day	Ref. No. 2
Lubricating oil	20 gallons/day	Ref. No. 2
Steel	79,000 lbs/yr	Ref. No. 1
Rubber (tires)	16,800 lbs/yr	Ref. No. 1

(2) Efficiency and Losses

- No physical losses of shale are anticipated for this option.
- Fuel consumption is considered a loss from the module.

(e) Data sources

(1) Private communications with mining and engineering companies.
(2) Estimated by CSMRI.

Module Energy Summary:

(1) Principal Energy Input
Type: Crushed oil shale, any grade
Quantity, units: Btu output = Btu input
Btu/unit: Consistent with shale grade
Btu input: Consistent with shale grade and quantity

(2) Principal Energy Loss
None

(3) Principal Energy Output
Type: Crushed oil shale
Quantity: Btu output = Btu input into retort; calculate tonnage as appropriate.

(4) Process Efficiency
100%

(5) Principal Energy to be used within Process Boundary
None

4.1.3 Retorting

In order to obtain useful products from oil shale, the shale must be heated to about 900°F. At this temperature the kerogen decomposes to form oil, gas, and a carboraceous residue. When carried out above-ground, this pyrolysis process, more commonly referred to as retorting, can be carried out by a variety of methods in a variety of vessels, called retorts. Each of these surface retorts is unique in design, but the methods by which the shale is heating are basicially similar and can be grouped according to the following general types:

- o Direct heated-gas flow.
- o Indirect heated-gas flow.
- o Indirect heated-hot solids.

In a direct heated-gas flow retort, heat for retorting is provided by a stream of hot gas that flows through the retort. The gas stream is composed of the products of combustion that are formed when (1) a portion of the gas product from the retort is burned with air or (2) the carbonaceous residue on the retorted shale is burned with air. The gas flow through the retort can be either counter-current or cross-current, relative to the direction of shale flow through the retort. A general characteristic of direct heated-gas flow retorts is that the gas product has a heating value of less than 200 Btu/scf. The reason is that the combustion air that is introduced into the retort carries with it a significant amount of nitrogen that passes out of the retort with the gas product. The nitrogen has no heating value associated with it and serves only to dilute the product gas.

In an indirect heated-gas flow retort, heat for retorting is provided by a stream of hot gas product that is heated in an external furnace. Fuel for the external furnace is provided by the gas product from the retort. Since the heat carrying gas is not mixed with air before being injected back into the retort, the gas product is not diluted by nitrogen and, therefore, has a higher heating value than the gas product from a direct heated, gas flow retort. The heating value of the gas product from an indirect heated, gas flow retort is generally 800 Btu/scf or greater.

In an indirect heated-hot solids retort, heat for retorting is provided by a stream of hot circulating solid material. This solid material can be retorted shale, sand, or any other material capable of withstanding the high temperatures that are required for oil shale retorting.

In addition to being processed aboveground, oil shale can be retorted in place, or in-situ. Two techniques are presently being investigated for in-situ retorting of oil shale: the modified in-situ (MIS) and true in-situ (TIS) techniques.

Descriptions and examples of each of these techniques for obtaining oil from oil shale, as well as general energy requirements for each, are presented in the sections that follow.

4.1.3.1 Direct Heated, Gas Flow Retorts: Paraho and Superior

Two examples of direct heated, gas flow retorts are the Paraho vertical kiln retort and the Superior circular grate retort. The following section presents discussion of each of these retorts.

The Paraho retort is a refractory-lined vertical kiln in which a moving bed of crushed shale flowing downward through the kiln is contacted with a counter-current flow of hot gases that pyrolyze the organic material in the shale and convey the resulting vapors out the top of the retort. Raw shale is fed into the top of the retort by means of a rotating "pant-leg" distributor, as shown in Figure 4.5. As the shale flows downward through the retort, it passes through a series of temperature zones, depicted in Figure 4.5, that determine the stage of the retorting process in which the shale is engaged. The first temperature zone that the shale encounters as it passes down the retort is the preheating or mist formation zone in which heat is transferred from the rising gases to the cool incoming shale. This has the effect of preheating the shale prior to retorting, thereby increasing overall thermal efficiency. The second zone through which the shale passes is the retorting zone. In this zone, the shale encounters hot gases rising from the combustion zone in the direct heated mode or from the heating zone in the indirect heated mode. The hot gases heat the shale to a temperature that is sufficiently high to pyrolyze the kerogen. The resulting vapors are then swept from the retort by the upward flow of gases.

The next zone into which the shale passes is that in which the heat for retorting is developed. This portion of the retort distinguishes the direct heated mode of operation from the indirect heated. In the direct heated mode, sufficient air is injected into the retort to cause combustion of the residual carbon present on the retorted shale. In some cases, additional heat is supplied by injecting and burning a portion of the product gas. The indirect heated mode of the Paraho retort is discussed in more detail in the next section.

After passing through the combustion zone, the shale passes through the cooling zone. In this zone, heat is transferred from the hot shale to a stream of cool product gas that is injected at the bottom of the retort. The cooled shale then passes out the bottom of the retort through a patented grate mechanism used to control the velocity of the shale through the retort and also to maintain an even downward flow of shale over the cross section of the retort.

In the direct heated mode, a significant quantity of air is injected into the retort and burned. The resulting combustion gases dilute the product gas causing it to have a very low heating value. As shown in Table 4.5, gas produced in the direct heated mode has a higher heating value (HHV) of 102 Btu/scf. This low heating value results in the product gas being used exclusively as fuel for the processing plant.

Table 4.5 also shows the properties of the crude shale oil produced in the direct heated mode. As with crude shale oil produced by other retorting processes, the high concentration of nitrogen and metals relative to conventional crude oil results is significantly more severe refining techniques being required to produce usable fuels.

The retort that The Superior Oil Company proposes to use is a circular traveling grate, a conceptual view of which is shown in Figure 4.6. In this process, a layer of shale that has been crushed and screened to between 1/4 and 4 in. is placed in a continuous grate. The grate is designed so that gases can

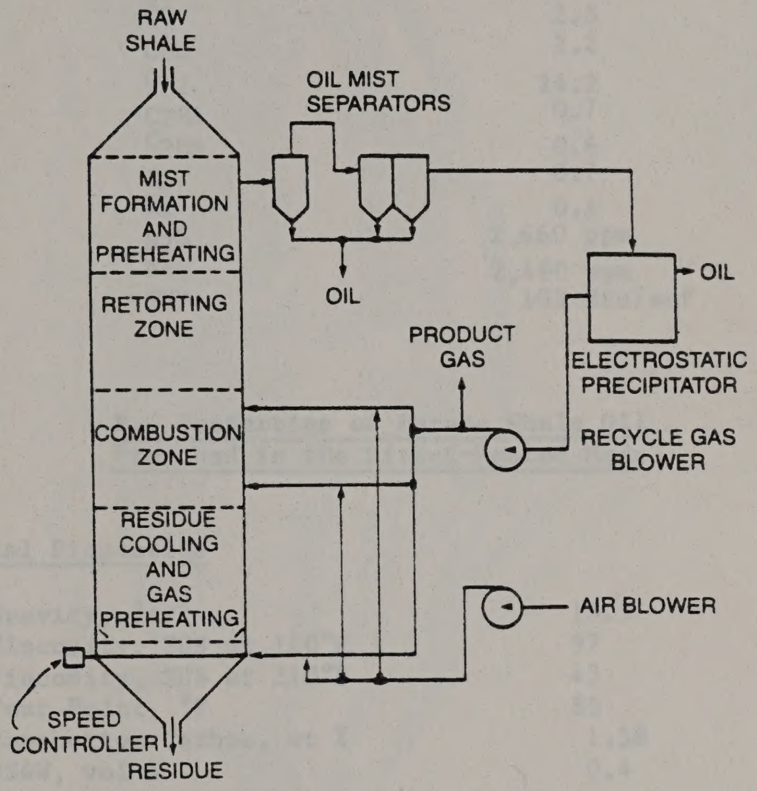


FIGURE 4.5

Paraho Retort-Direct Heated Mode

TABLE 4.5

A. Properties of Product Gas Produced in the Paraho Retort Direct Heated Mode

Component	Volume % dry basis
H_2	2.5
N_2	65.7
O_2	0
CO	2.5
CH_4	2.2
CO_2	24.2
C_2H_4	0.7
C_2H_6	0.6
C_3	0.7
C_4	0.4
H_2S	2,660 ppm
NH_3	2,490 ppm
HHV	102 Btu/scf

B. Properties of Paraho Shale Oil Produced in the Direct-Heated Mode

Physical Properties

Gravity, °API	19.3
Viscosity, SUS at 140°F	97
Viscosity, SUS at 210°F	43
Pour Point, °F	85
Ramsbottom Carbon, wt %	1.38
BS&W, vol %	0.4

Ultimate Analysis

Carbon, wt%	84.90
Hydrogen, wt %	11.50
Oxygen, wt %	1.40
Nitrogen, wt %	2.19
Sulfur, wt %	0.61

Selected Metal Concentration

Arsenic, ppm	19.6
Nickel, ppm	2.5
Iron, ppm	71.2

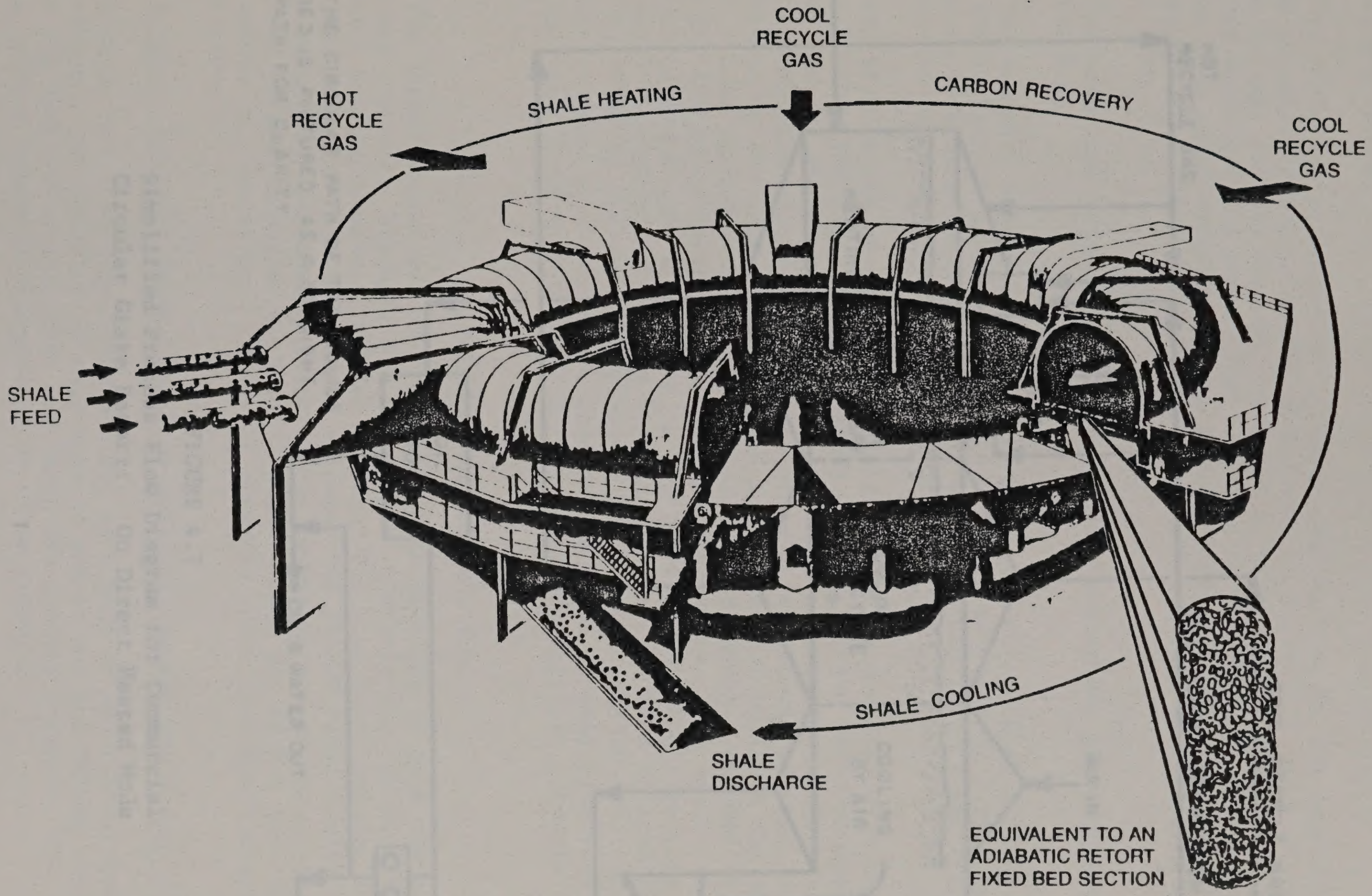


FIGURE 4.6

Conceptual View of Superior Retort

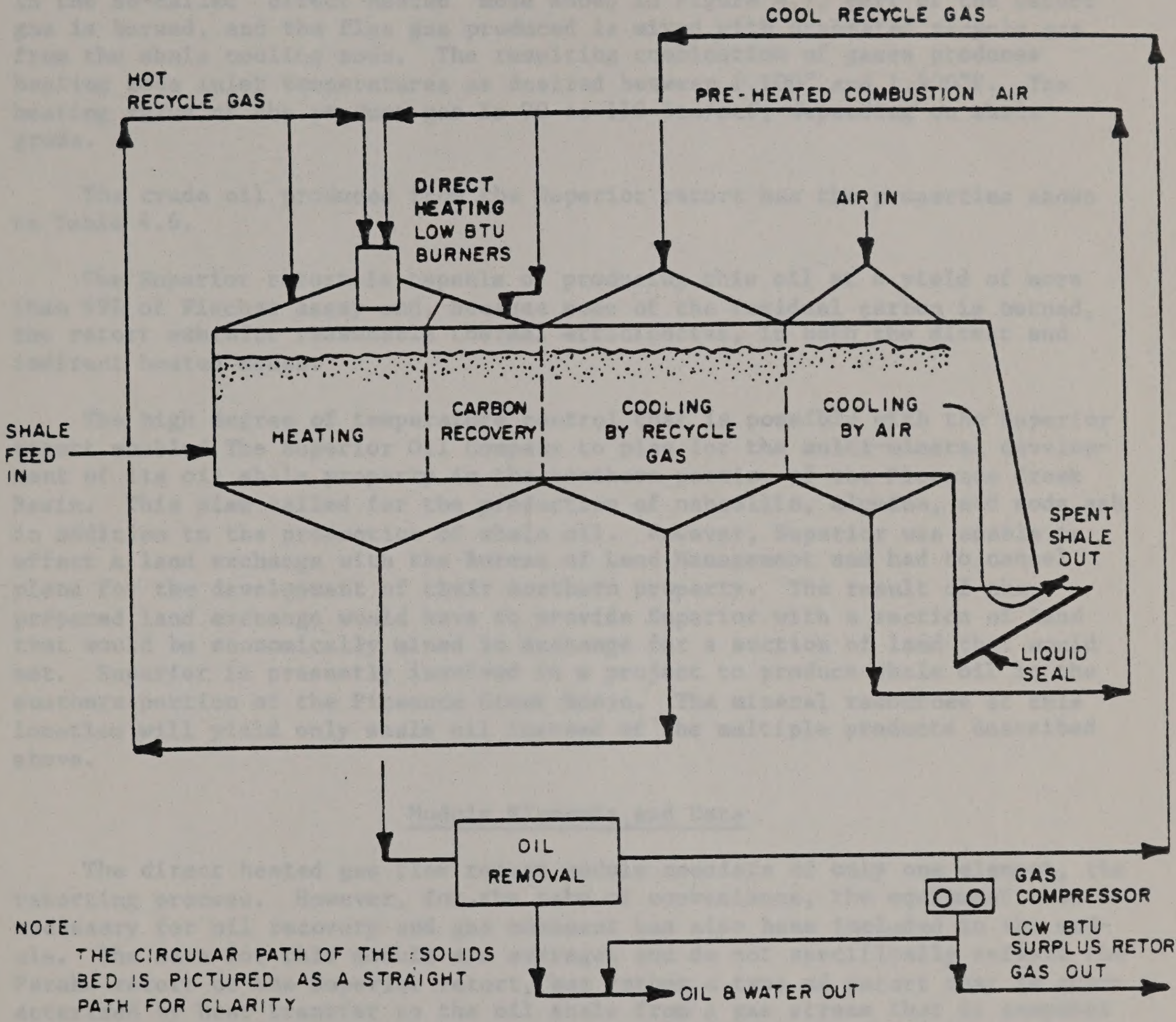


FIGURE 4.7

Simplified Process Flow Diagram for Commercial Circular Grate Retort: On Direct Heated Mode

flow through it and the shale bed. As the shale is carried through the retort by the grate, it passes through several zones in which it is heated, retorted, cooled, and dumped.

The shale can be heated by either of two methods in the Superior retort. In the so-called "direct heated" mode shown in Figure 4.7, part of the retort gas is burned, and the flue gas produced is mixed with preheated recycle gas from the shale cooling zone. The resulting combination of gases produces heating zone inlet temperatures as desired between 1,100° and 1,500°F. The heating value of the product gas is 90 to 150 Btu/scf, depending on shale grade.

The crude oil produced from the Superior retort has the properties shown in Table 4.6.

The Superior retort is capable of producing this oil at a yield of more than 99% of Fischer assay and, because some of the residual carbon is burned, the retort exhibits reasonable thermal efficiencies, in both the direct and indirect heated modes.

The high degree of temperature control that is possible with the Superior retort enabled The Superior Oil Company to plan for the multi-mineral development of its oil shale property in the northern portion of the Piceance Creek Basin. This plan called for the production of nahcolite, alumina, and soda ash in addition to the production of shale oil. However, Superior was unable to effect a land exchange with the Bureau of Land Management and had to cancel plans for the development of their northern property. The result of the prepared land exchange would have to provide Superior with a section of land that would be economically mined in exchange for a section of land that would not. Superior is presently involved in a project to produce shale oil in the southern portion of the Piceance Creek Basin. The mineral resources at this location will yield only shale oil instead of the multiple products described above.

Module Elements and Data

The direct heated gas flow retort module consists of only one element, the retorting process. However, for the sake of convenience, the equipment that is necessary for oil recovery and gas movement has also been included in the module. The data for this module are averages and do not specifically reflect the Paraho retort or the Superior retort, but rather a type of retort that is characterized by heat transfer to the oil shale from a gas stream that is composed of products of combustion. Table 4.7 presents these data and the associated assumptions.

4.1.3.2 Indirect Heated Gas Flow Retorts: Paraho and Union "B"

Section 4.1.3 briefly described the principle of an indirect heated gas flow retort. Two examples of this type of retort are the Paraho retort operated in the indirect heated mode and Union Oil Company's retort "B". The following section presents discussions of these retorts.

TABLE 4.6

Physical Properties of Superior Crude Shale Oil

Gravity, °API	18-25
Viscosity, SUS at 100°F	100-200
Pour Point, °F	70-90
Nitrogen, wt %	1.8-2.1
Sulfur, wt %	0.7-0.9

TABLE 4.7

Module: Direct Heated Gas Flow Retorts
(Paraho and Superior)

(a) Equipment, facilities

Retorts
Gas blowers
Electrostatic precipitators
Oil mist separators
Product pumps

(b) Assumptions

(1) Crude shale oil production from the retort is 50,000 barrels per day.
(2) Raw shale feed is 78,000 tons per day of raw shale with a Fischer assay of 30 gpt.
(3) Oil recovery is roughly 90% of Fischer assay.
(4) Air feed to the retort is 18,537 tons per day

Spent shale	63,500 tons/day
Product gas	23,105 tons/day
Retort water	3,285 tons/day
Dust	86 tons/day

(6) Operation is 24 hours per day, 365 days per year.

(c) Guidelines on data

(1) Data are for production of 50,000 barrels/day of crude shale.
(2) Data can be scaled for other production rates by simple ratio.
(3) The materials data reflect total requirements for a 20-year pro-
(3) ject lifetime. They are not annual or daily usage figures.
(4) Approximately 1500 tons of product gas per day are recycled within the modules. The heating value of this gas is estimated at 900 Btu/lb.

(d) Data

(1) Direct energy to produce 50,000 barrels/day of crude shale oil:

Electricity	813,300 kwh/day	Ref. No. 2,5

(2) Materials to produce 50,000 barrels/day of crude shale oil:

Structural steel	17,640 tons	Ref. No. 5
Concrete	52,240 tons	Ref. No. 5
Equipment steel	30,840 tons	Ref. No. 5

TABLE 4.7

Continued

(3) Efficiency and losses

- Recovery of shale oil is equal to approximately 90% of Fischer assay.
- The electrical energy input to the retort is considered a loss from the module.
- The recycled product gas stream is considered a loss from the module. At 900 Btu/lb, the energy loss is estimated as

$$\frac{1500 \text{ tons}}{\text{day}} \times \frac{2000 \text{ lbs}}{\text{ton}} \times \frac{900 \text{ Btu}}{\text{lb}} = 2.70 \times 10^9 \text{ Btu/day}$$

(e) Data sources

(1) Kunchal, S.K., 1975, Energy requirements in an oil shale industry: Based on Paraho's direct combustion retorting process, in Quarterly of the Colorado School of Mines: Golden, Colorado, vol. 70, no. 3, p. 21-29.
(2) McKee, J.M., and Kunchal, S.K., 1976, Energy and water requirements for an oil shale plant based on Paraho processes, in Quarterly of the Colorado School of Mines: Golden, Colorado, vol. 71, no. 4, p. 49-64,.
(3) Knight, J.H., and Fishback, J.W., 1979, Superior's circular grate oil shale retorting process, in Twelfth Oil Shale Symposium Proceedings: Golden, Colorado, Colorado School ofMines, p. 1-16.
(4) Jones, J.B., and Heistand, R.N., 1979, Recent Paraho operations, in Twelfth Oil Shale Symposium Proceedings: Golden, Colorado, Colorado School of Mines, p. 184-194.
(5) Private communication with a major oil shale developer.

Module Energy Summary:

(1) Principal Energy Input
Type: 30 gal/ton oil shale, crushed
Quantity, units: 78,000 tons/day
Btu/unit: 2,750 Btu/lb = 5.50×10^6 Btu/ton
Btu input: 429.0×10^9 Btu/day

(2) Principal Energy Loss
89.8×10^9 Btu/day

(3) Principal Energy Output
Type: Crude oil shale
Quantity: 50,000 bbl/day = 300.3×10^9 Btu/day
Type: Product gas
Quantity: 21,605 tons/day = 38.9×10^9 Btu/day (net)

TABLE 4.7

Continued

(4) Process Efficiency
79.1%

(5) Principal Energy to be used within Process Boundary
38.9 x 10^9 Btu/day Gas Principal Energy Output (see item (3) above) is available for use within trajectory process boundary; this is net output of gas from module after some gas (1,500 tons/day) is used within this module.

A description of the Paraho retort operated in the direct heated mode is presented in section 4.1.3.1. Operation of the Paraho retort in the indirect heated mode is basically the same with the following significant difference. To provide heat for retorting in the indirect heat mode, a stream of product gas is heated in an external gas heater and then injected into the retort, as shown in Figure 4.8. Fuel for the external gas heater is supplied by a stream from the product gas line.

When the Paraho retort is operated in the indirect heated mode, a valuable source of energy, in the form of the residual carbon left on the spent shale, is not utilized. This lost energy is compensated for by burning a portion of the product gas, thus decreasing the net energy yield from the process. However, this residual carbon may be recovered in a commercial operation through direct combustion or gasification in an external unit.

Because no air is injected into the retort when operated in the indirect heated mode, the product gas has a significantly higher heating value, as shown in Table 4.8. The absence of the large quantity of nitrogen results in a higher heating value (HHV) of 885 Btu/scf.

Table 4.8 also shows the properties of the crude shale oil produced in the indirect heated mode. The high concentration of nitrogen charcterizes this material as shale oil rather than conventional crude oil.

A second example of an indirect heated gas flow retort is Retort B, developed by Union Oil Company of California. Retort B is one of several retorts developed by Union that rely on the operation of a solids pump that provides for the upward flow of solids and the downward flow of gases through a retort having the shape of an inverted cone.

As shown in Figure 4.9, crushed and screened oil shale from the feed bin flows through two feed chutes to the solids pump. Shale oil acts as an hydraulic seal to maintain retort pressure and to prevent the escape of product gas from the shale feed chutes. Recycle gas heated in an external furnace provides the heat for retorting. The temperature of the recycle gas is maintained between 950° and 1000°F.

Gasification and combustion of the carbon residue on the spent shale can be performed in a separate vessel. If this is done, the resulting hot flue gas can be used to heat the recycle gas stream. This would eliminate the need for the external furnace as well as the need to burn a significant portion of the retort product gas.

Because no air is introduced into the retort, the product gas exhibits a high heating value, as shown in Table 4.9. The properties of the crude shale oil are presented in Table 4.9.

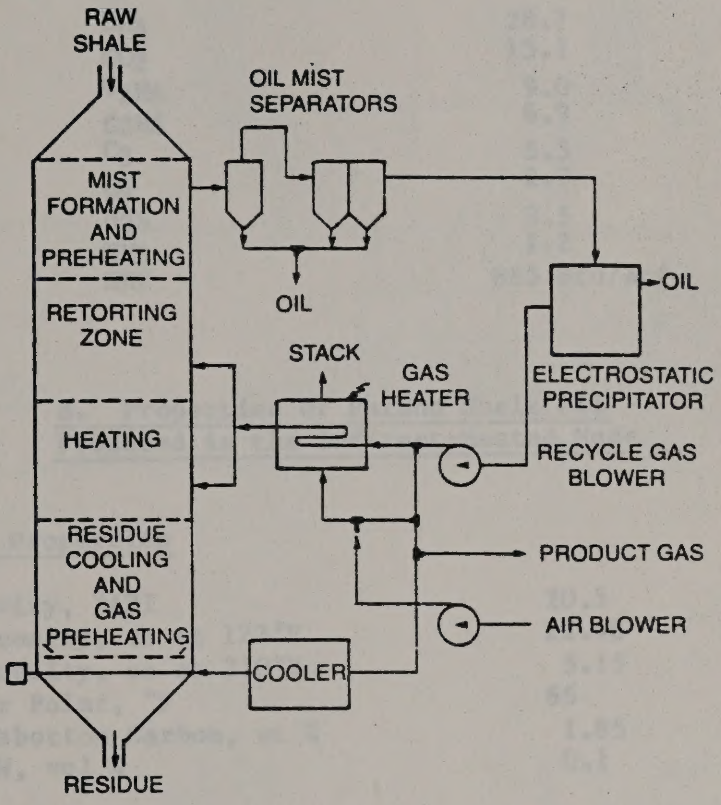


FIGURE 4.8

Paraho Retort-Indirect Heated Mode

TABLE 4.8

A. Properties of Product Gas Produced in the Paraho Retort Indirect Heated Mode

Component	Volume % dry basis
H_2	24.8
N_2	0.7
O_2	0
CO	2.6
CH_4	28.7
CO_2	15.1
C_2H_4	9.0
C_2H_6	6.9
C_3	5.5
C_4	2.0
H_2S	3.5
NH_3	1.2
HHV	885 Btu/scf

B. Properties of Paraho Shale Oil Produced in the Indirect-Heated Mode

Physical Properties

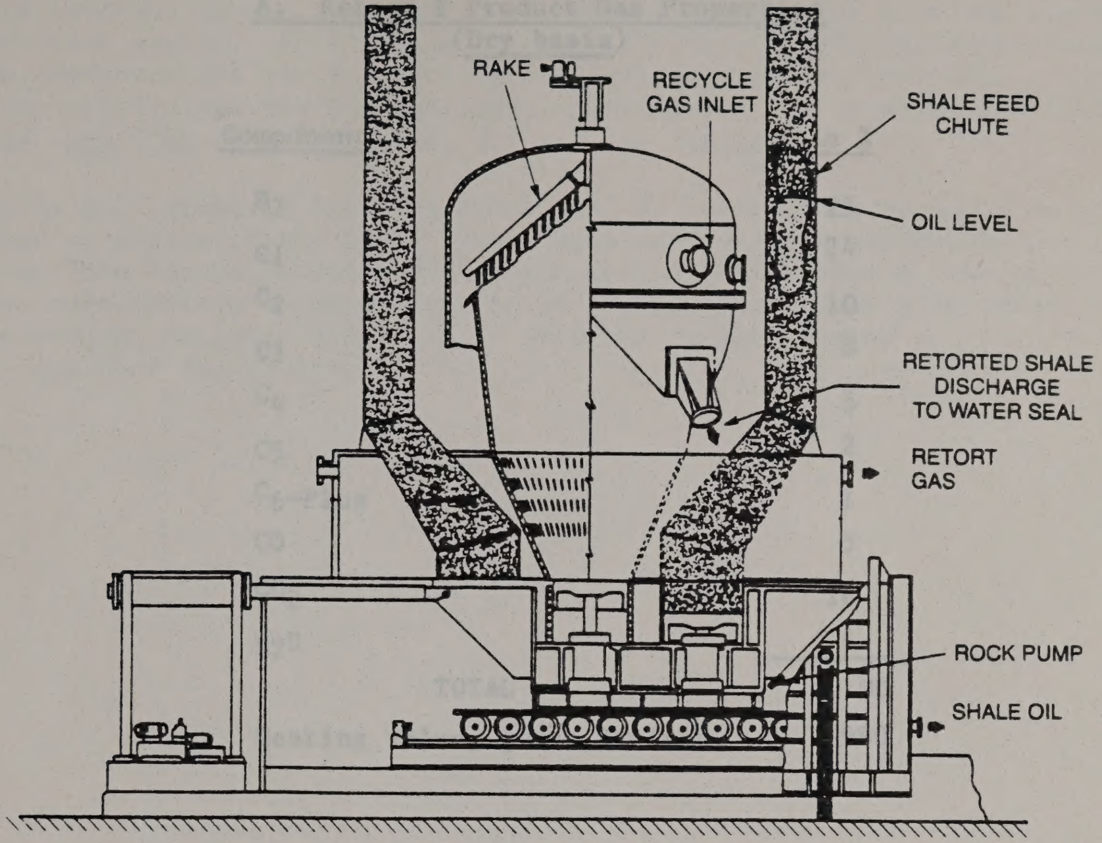
Gravity, °API	20.5
Viscosity, cs at 122°F	22.48
Viscosity, cs at 210°F	5.15
Pour Point, °F	65
Ramsbottom Carbon, wt %	1.85
BS&W, vol %	0.1

Ultimate Analysis

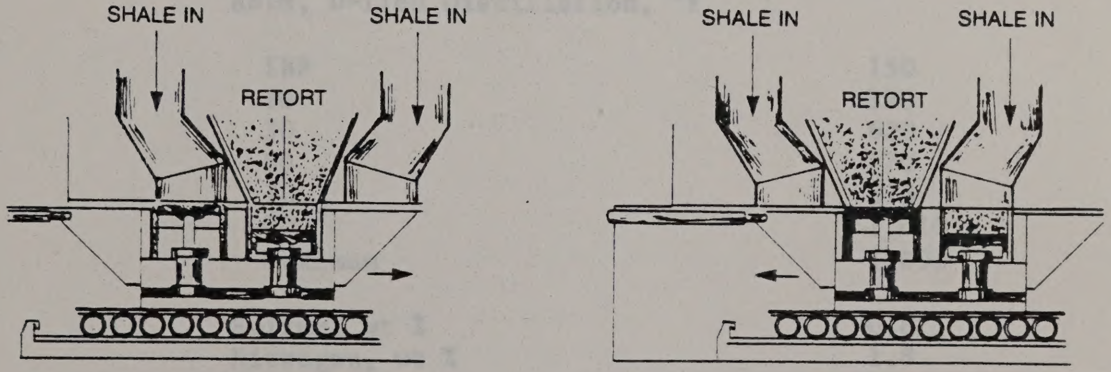
Carbon, wt%	84.58
Hydrogen, wt %	11.42
Oxygen, wt %	1.19
Nitrogen, wt %	2.15
Sulfur, wt %	0.63

Selected Metal Concentration

Arsenic, ppm	26.5
Nickel, ppm	2.8
Iron, ppm	68
Vanadium, ppm	0.3



A. The Retorting System



B. Rock Pump Detail

FIGURE 4.9

Union Oil Retort B

TABLE 4.9

A. Retort B Product Gas Properties
(Dry basis)

Component	Mole %
H_2	25
C1	24
C_2	10
C3	8
C_4	5
C5	2
C_6-Plus	1
CO	5
CO_2	16
H_2S	4
TOTAL	100
Heating value, gross Btu/scf	980

B. Retort B Crude Shale Oil Properties

Gravity, °API	22.2
ASTM, D-1160 Distillation, °F	
IBP	150
10	390
30	620
50	770
70	875
90	1,010
Maximum	1,095
Sulfur, wt %	0.8
Nitrogen, wt %	1.8
Oxygen, wt %	0.9
Fischer Water, wt %	0.2
Pour Point, °F	60
Arsenic, ppm	50
Conradson Carbon Residue, wt %	2.1
Heating Value, gross, M Btu/gal	142

Module Elements and Data

The indirect heated gas flow retort module consists of only one element: the retorting system. This system includes the retort, oil collection equipmet such as demisters and electrostatic precipitators, all gas circulation equipment, and recycle gas heating equipment. Facilities for crushing the feed shale or upgrading the crude shale oil are not included.

Table 4.10 presents data for the module as well as the assumptions that were used to arrive at the data. These data are averages and do no specifically reflect the Paraho retort or Union's Retort B, but rather a type of retort that is characterized by heat transfer to the oil shale from a recycled product gas stream that has been heated in an external furnace fueled by a stream of product gas from the retort.

TABLE 4.10

Module: Indirect Heated Gas Flow Retorts (Paraho and Union Retort B)

(a) Equipment, facilities

Retorts
Gas blowers
Electrostatic precipitators
Oil mist separators
Product pumps
Gas fired furnaces
Heat exchangers

(b) Assumptions

(1) The data are for the production of 50,000 barrels of crude shale oil per day.
(2) No combustion or gasification of the carbon residue on the spent shale takes place.
(3) The carbon residue is about 3% to 4% by weight.
(4) The product gas from the retort has a heating value of 800 Btu/scf.
(5) The crude shale oil has a heating value of 142,000 Btu/gallon.
(6) Raw shale feed is 69,000 tons of oil shale per day with a Fischer assay of 32 gpt.
(7) Oil recovery is roughly 95% of Fischer assay.
(8) Product streams in addition to crude shale oil are:

Spent shale	52,700 tpd
Product gas	8.83×10^{6} scf/day
Retort water (sour)	16,300 gallons/day

(c) Guidelines on data

(1) Data are for the production of 50,000 barrels of crude shale oil per day.
(2) Data can be scaled for different production rates by simple ratio.
(3) The materials data reflect total requirements for a 20-year project lifetime. They are not annual or daily usage figures.
(4) Approximately 40.8×10^{6} scf of product gas per day are recycled within the module as furnace fuel.

(d) Data

(1) Direct energy to produce 50,000 barrels of crude shale oil per day:

Electricity	1.12×10^{6} kwh/day	Ref. No. 2,3

TABLE 4.10

Continued

(2) Materials to produce 50,000 barrels of crude shale oil per day:

Lumber	320 tons	Ref. No. 5
Structural steel	17,640 tons	Ref. No. 5
Concrete	52,240 tons	Ref. No. 5
Equipment steel	30,840 tons	Ref. No. 5

(3) Efficiency and losses

- o Recovery of shale oil is equal to approximately 90% of Fischer assay.
- o The electrical energy input to the retort is considered a loss from the module.
- o The production gas stream that fuels the external furnace is considered a loss from the module. At 800 Btu/scf, the energy loss is estimated to be:

$$40.8 \text{x} 10^6 \text{ scf/day} \times 800 \text{ Btu/scf} = 32.64 \times 10^9 \text{ Btu/day}$$

- o The energy associated with the carbon residue on the spent shale is considered a loss since it has been assumed that no recovery of this energy takes place. At 1.28×10^6 Btu/ton of spent shale, the energy loss is estimated to be:

$$52{,}700 \ \frac{\text{tons}}{\text{day}} \times 1.27 \times 10^6 \ \frac{\text{Btu}}{\text{tons}} = 67.46 \times 10^9 \ \frac{\text{Btu}}{\text{day}}$$

(e) Data sources

(1) Kunchal, S.K., 1975, Energy requirements in an oil shale industry: Based on Paraho's direct combustion retorting process, in Quarterly of the Colorado School of Mines: Golden, Colorado, vol. 70, no. 3, p. 21-29.

(2) McKee, J.M., and Kunchal, S.K., 1976, Energy and water requirements for an oil shale plant based on Paraho processes, in Quarterly of the Colorado School of Mines: Golden, Colorado, vol. 71, no. 4, p. 49-64,.

(3) Duir, J.F., Deering, R.F., and Jackson, H.R., 1977, New developments in oil shale retorting by Union Oil Company: Chicago, Illinois, Paper presented at the 42nd Midyear Meeting of the API Refining Department.

(4) TRW Energy Systems Group, 1979, Oil shale data book: McLean, Virginia, TRW Energy Systems Group, 439 p.

(5) Griffis, R.L., and Baughman, G.L., 1981, Parameters affecting the characteristics of oil shale-derived fuels: Golden, Colorado, Colorado School of Mines Research Institute, 145 p.

(6) Private communication with a major oil shale developer.

TABLE 4.10

Continued

Module Energy Summary:

(1) Principal Energy Input
Type: 30 gal/ton oil shale, crushed
Quantity, units: 71,400 tons/day
Btu/unit: 2,750 Btu/lb = 5.50 x 10^6 Btu/ton
Btu input: 392.7 x 10^9 Btu/day

(2) Principal Energy Loss
66.19 x 10^9 Btu/day (including spent shale)

(3) Principal Energy Output
Type: Crushed shale oil
Quantity: 50,000 BPD = 300.3 x 10^9 Btu/day
Type: Product gas

(4) Process Efficiency
83.1%

(5) Principal Energy to be used within Process Boundary
Type: Product gas
Quanity: 26.17 x 10^9 Btu/day

4.1.3.3 Indirect Heated Hot Solids Retorts: TOSCO II and Lurgi-Ruhrgas

Two examples of indirect heated hot solids retorts are the TOSCO II retort and the Lurgi-Ruhrgas retort. The following section presents discussions of each of these retorts.

The TOSCO II retort is an indirectly heated retort in which hot ceramic balls carry heat to finely crushed oil shale. The basic configuration of the process is shown in Figure 4.10. Raw shale, crushed to minus 1/2 in., is fed to the retorting train and preheated to about 500°F by direct heat exchange with flue gas from the ball heater. The preheated raw shale is separated from the flue gas in settling chambers and cyclones and sent to a rotating drum retort. The flue gas is incinerated within the preheat system to reduce the amount of trace hydrocarbons in the discharge flue gas.

Pyrolysis is accomplished in the retort by solid-to-solid heat exchange between the preheated shale and hot ceramic balls that enter the pyrolysis drum at about 1,200°F. The balls are heated in a direct fired heater using product gas for fuel. The rotating pyrolysis drum provides intimate contact between the shale and the ceramic balls. Pyrolysis takes place when the shale temperature reaches approximately 900°F. The retort products of balls, spent shale, and hydrocarbon vapors pass from the pyrolysis drum to a separation vessel. The hydrocarbon vapors are sent to further processing, which will be discussed later. The ceramic balls and spent shale pass over a rotating screen called a trommel. The shale, which has been thoroughly crushed during retorting, falls through holes in the trommel and passes to a retorting drum steam generator where it is cooled to about 300°F. The cooled shale is then moistened to approximately 14% and sent to disposal.

The ceramic balls pass over the trommel and fall to a vessel where dust is removed from the surface. The dust-free balls are then circulated back to the ball heater by means of a bucket elevator.

Crude shale oil from the TOSCO II process exhibits the properties shown in Table 4.11. As with other crude shale oils, this oil contains a significantly higher amount of nitrogen than conventional petroleum crudes do. It is worth noting that the Final Environmental Impact Statement for the Colony Development Operation describes a plan to include shale oil upgrading facilities as part of the retorting plant site.

In general, oil yields from a TOSCO II retort are quite high, consistently producing over 100% of Fischer assay. However, because the energy in the spent shale carbon is not utilized, thermal efficiencies are low. A significant portion of the product gas is burned in the ball heater. The low energy efficiency could be improved if TOSCO develops, to a practical point, the processes it has patented to burn or gasify the retorted shale, providing fuel for the ball heater.

The Lurgi-Ruhrgas retorting process, shown schematically in Figure 4.11 utilizes solid heat carriers to provide the necessary heat for pyrolysis. Raw oil shale, crushed to approximately minus 1/4 in., is fed to the screw mixer where it is mixed with six to eight times that quantity of hot solids from the collection bin. The temperature of the raw shale increases to about 500°C within a few seconds, effectively pyrolyzing the organic matter in the shale.

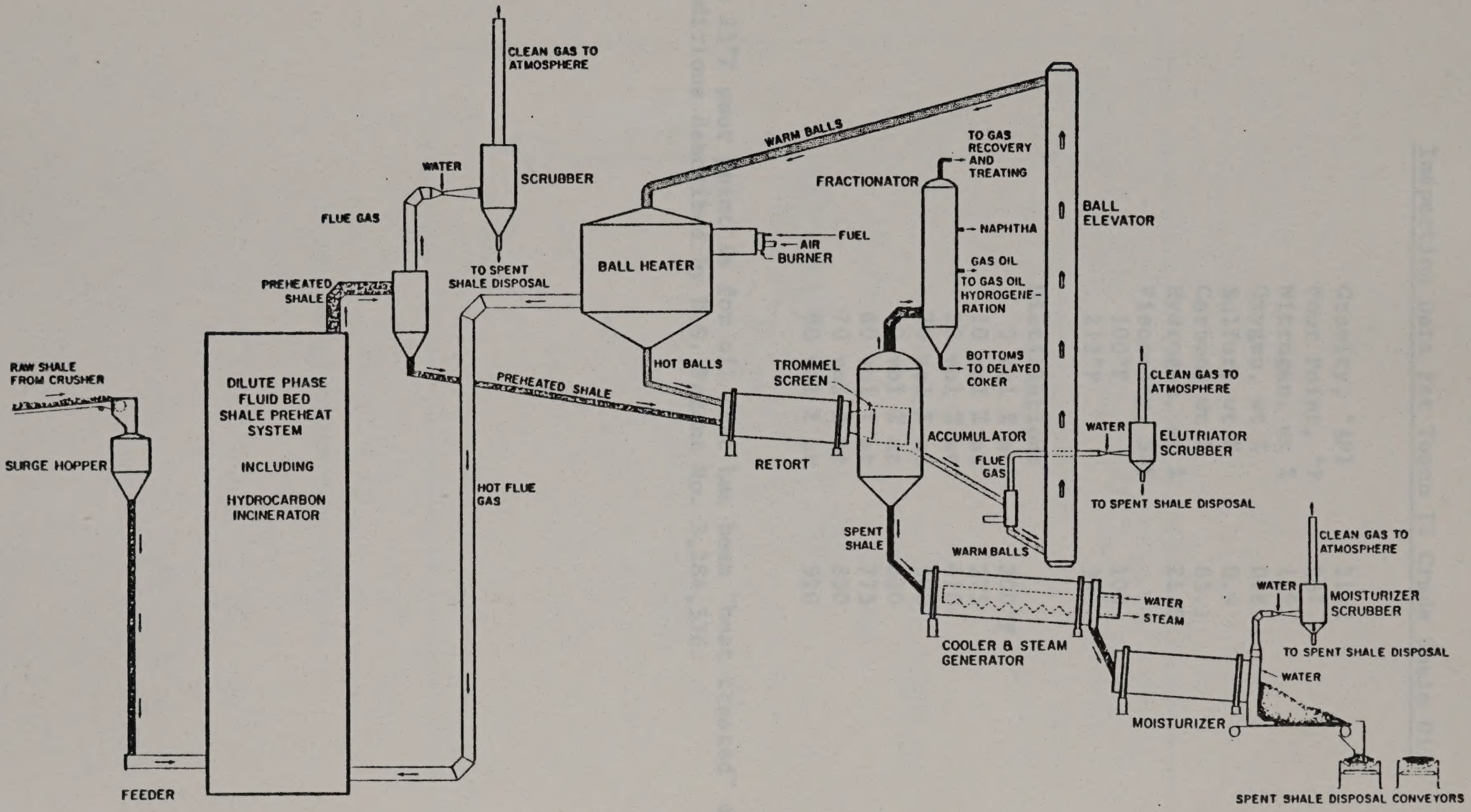


FIGURE 4.10

TOSCO II Retorting Process

TABLE 4.11

Inspection Data for Tosco II Crude Shale Oil

Gravity, °API	21.2
Pour Point, °F	25[1]
Nitrogen, wt %	1.9
Oxygen, wt %	0.8
Sulfur, wt %	0.9
Carbon, wt %	85.1
Hydrogen, wt %	21.6
Viscosity, SUS	
100°F	106
212°F	39
Distillation:	
5 vol % at	200°F
10 vol % at	275
20 vol % at	410
30 vol % at	500
40 vol % at	620
60 vol % at	775
70 vol % at	850
80 vol % at	920

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[1] The 25°F pour point is for oil that has been "heat treated" as per conditions described by U.S. Patent No. 3,284,336.

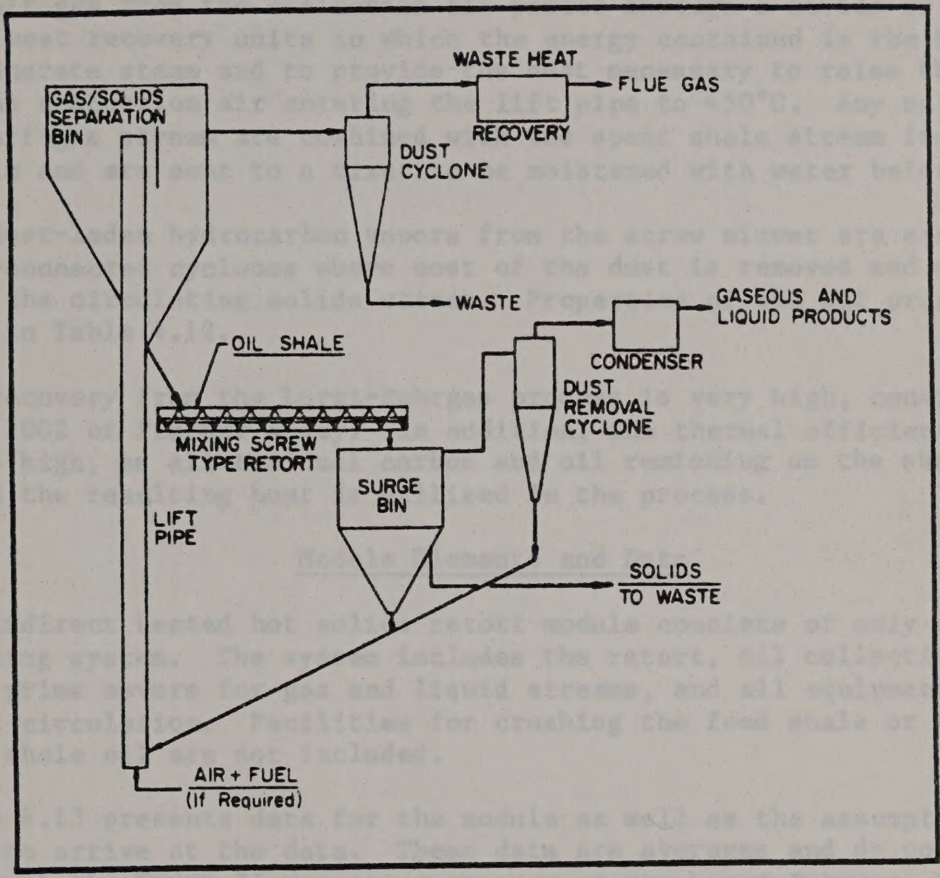


FIGURE 4.11

Lurgi-Ruhrgas Retorting Process

The hot spent shale exits the screw mixer and falls to the lower section of the lift pipe where it contacts combustion air that has been preheated to about 450°C in the waste heat recovery portion of the process. The solids are lifted up the lift pipe by the combustion air while, at the same time, the carbon residue is burned off the spent shale. The gas/solid mixture separates in the collection bin after having reached a temperature of about 650°C. The heated solids are then mixed with incoming raw shale, and the cycle continues. Excess solids are removed from the system after having been burned in the lift pipe. In this way, all of the fuel available in the raw shale is either produced as product oil or is used in the process, as is the case with the residual carbon.

The off gas from the collection bin passes through a series of dedusting and waste heat recovery units in which the energy contained in the hot gas is used to generate steam and to provide the heat necessary to raise the temperature of the combustion air entering the lift pipe to 450°C. Any solids removed from the off-gas stream are combined with the spent shale stream from the collection bin and are sent to a mixer to be moistened with water before disposal.

The dust-laden hydrocarbon vapors from the screw mixwer are sent to a pair of series-connected cyclones where most of the dust is removed and then returned to the circulating solids stream. Properties of the oil product are presented in Table 4.12.

Oil recovery from the Lurgi-Ruhrgas process is very high, consistently exceeding 100% of Fischer assay. In addition, the thermal efficiency of the process is high, as all residual carbon and oil remianing on the shale is burned and the resulting heat is utilized in the process.

Module Elements and Data

The indirect heated hot solids retort module consists of only one element: the retorting system. The system includes the retort, oil collection equipment, all prime movers for gas and liquid streams, and all equipment necessary for solids circulation. Facilities for crushing the feed shale or upgrading the crude shale oil are not included.

Table 4.13 presents data for the module as well as the assumptions that were used to arrive at the data. These data are averages and do not specifically reflect the TOSCO II retorting process or the Lurgi-Ruhrgas, but rather a type of retort that is characterized by heat transfer to the oil shale from a hot stream of recycled solids.

4.1.3.4 Modified In Situ (MIS) Retorts

Preparation of a MIS retort was described briefly in Section 4.1.1.3. This section presents a description of oil shale retorting in a MIS retort.

After blasting has been completed, the access tunnels are sealed and an injection hole is drilled from the surface (or from a higher mining level) to the top of the rubble pile. To retort the shale, a small amount of outside fuel is ignited at the top of the rubblized shale to heat it to almost 900°F. After a specified amount of shale has been heated, the burners are removed, and combustion is continued by injecting air into the top of the retort and burning the carbon residue left on the shale after it has been retorted. This process

TABLE 4.12

Shale Oil Analysis from Lurgi-Ruhrgas Process

Gravity, °API	18.7
Pour Point, °F	64
Carbon, wt %	85.2
Hydrogen, wt %	10.7
Nitrogen, wt %	2.1
Oxygen, wt %	1.1
Sulfur, wt %	0.9
Viscosity	
CS @ 86°F	22.3
CS @ 122°F	10.3
Distillation:	
Initial Boiling Point	205°F
5 vol %	295
10 vol %	338
20 vol %	428
30 vol %	500
40 vol %	583
50 vol %	657
60 vol %	739
70 vol %	820
80 vol %	914
85 vol %	946
Heating Value, $\frac{\text{Btu}}{\text{gal}}$	133,900

TABLE 4.13

Module: Indirect Heated Hot Solids Retorts
(TOSCO II and Lurgi-Ruhrgas)

(a) Equipment, facilities

Retorts
Gas compressors
Cyclones
Pumps
Electrostatic precipitators
Miscellaneous heat exchangers and pressure vessels

(b) Assumptions

(1) Net production from the retorting process is as follows:

Crude shale oil	50,000 BPS @ 6.01 x 10^6 Btu/bbl
Product gas	1370 tons/day @ 19.10 x 10^6 Btu/ton

(2) Operation is 24 hrs/day

(3) Only a portion of the residual carbon on the spent shale is burned to supply heat for retorting. The heating value of the spent shale is estimated at 200,000 Btu/ton. Approximately 57,120 tons of spent shale exit the retorting process.

(c) Guidelines on data

(1) Data are for a retorting process that produces 50,000 barrels of crude shale oil per day.

(2) The data may be adjusted to other production rates by using a simple ratio.

(d) Data

(1) Direct energy for the production of 50,000 barrels of crude shale oil per day:

Electricity	870,4500 kwh/day	Ref. No. 2,5

(2) Materials requirements for the production of 50,000 barrels of crude shale oil per day:

Lumber	320 tons	Ref. No. 5
Structural steel	17,640 tons	Ref. No. 5
Concrete	52,240 tons	Ref. No. 5
Equipment steel	30,840 tons	Ref. No. 5

(3) Efficiency and Losses

- Recovery of shale oil is equal to approximately 102% of Fischer assay.
- Overall process efficiency is 83.1%.

TABLE 4.13

Continued

- All electricity input is assumed to be a loss from the retort.
- Principal energy losses from the module are:

Spent Shale	)	
Retort water	)	Total loss = 39.39×10^9 Btu/day
Flue gas	)	

- Approximately 26.80×10^9 Btu/day of liquid fuel equivalent is recycled and consumed within the retort module. This energy is considered a loss from the module.

(e) Data sources

(1) Weiss, H.J., 1981, The retorting of oil shale by the Lurgi Ruhrgas process: Paper presented at 6th IIASA Resources Conference, Golden, Colorado, June 15-17.
(2) Lenhart, A.F., 1968, TOSCO process shale oil yields: Paper presented at AIME 97th National Meeting, February 27.
(3) Whitcombe, J.A., and Vawter, R.G., 1975, The TOSCO-II oil shale process: Prepared for American Institute of Chemical Engineers 79th National Meeting, March 16-20.
(4) Griffis, R.L., and Baughman, G.L., 1981, Parameters affecting the characteristics of oil shale-derived fuels: Golden, Colorado, Colorado School of Mines Research Institute, 145 p.
(5) Private communications with a major oil shale developer.

Module Energy Summary:

(1) Principal Energy Input
Type: 30 gal/ton oil shale, crushed
Quantity, units: 71,400 tons/day
Btu/unit: 2750 Btu/lb = 5.50×10^6 Btu/ton
Btu input: 392.7×10^9 Btu/day

(2) Principal Energy Loss
66.19×10^9 Btu/day (including spent shale)

(3) Principal Energy Output
Type: Crude shale oil
Quantity: 50,000 BPD = 300.3×10^9 Btu/day
Type: Product gas
Quantity: 1370 tons/day = 26.17×10^9 Btu/day

(4) Process Efficiency
83.1%

(5) Principal Energy to be used within Process Boundary
Type: Product gas
Quantity: 26.17×10^9 Btu/day

is similar to direct heated surface retorts, such as the Paraho process, except that the shale bed is fixed, and the combustion zone moves. The combustion zone advances down the retort preceded by the retorting zone in which kerogen is pyrolyzed. The resulting hydrocarbon vapors also move down the retort, condense when they contact as yet unheated shale, and the resulting liquid flows down the retort to a sump from which the oil is pumped to storage.

Occidental Petroleum Company (Oxy), one of the partners in the development of Federal tract C-b, has done a considerable amount of work in bringing MIS technology to a level of commercial readiness. Oxy has reported shale oil yields of about 60% of Fischer assay. The oil product from a MIS retort exhibits the properties shown in Table 4.14. The gas product can be used to ignite further retorts, or in the same manner as the product gas from direct heated gas flow surface retort.

Module Elements and Data

The modified in situ oil shale retorting module consists of one element: the retorting system. The element includes all facilities necessary for operation: compressors, pumps, etc. Data pertaining to energy consumption and materials requirements for an oil shale complex utilizing MIS technology are presented in Table 4.15.

4.1.3.5 True In Situ (TIS) Retorts

True in situ (TIS) retorting is a technique that is better suited to shale beds that are thin, deeply buried, or unsuitable for processing by other methods. This technique generally involves preparation of the retort without mining. A TIS technique that has been well presented in the literature is that being tested in Utah by Geokinetics, Inc.

The Geokinetics process uses a fracturing technique called surface uplift in which an explosive is injected into several wells and detonated to fracture the shale and to make it permeable to fluid flow. The shale is ignited by injecting air and fuel gas through one well, and the kerogen is pyrolyzed by the hot gas stream that flows through the shale bed.

Recovery of oil from within the retort boundaries is estimated at 50%. While the figure is low in comparison to other retorting processes, it is important to recall that this technique is designed to recover oil from oil shale deposits that would probably not be developed by other means.

Module Elements and Data

The true in situ retorting module consists of only one element: the retorting system. Because the entire operation of a TIS retort is very similar to the retorting mode of a MIS retort, the data that is presented in Section 4.1.3.4 has been scaled down to the maximum anticipated production using TIS technology: 2,000 barrels of crude shale oil per day. These data and the associated assumptions are presented in Table 4.16.

TABLE 4.14

Properties of Shale Oil from Occidental In Situ Process

Gravity, °API	25
Pour Point, °F	70
Viscosity, SUS at 100°F	70
Nitrogen, wt %	1.5
Sulfur, wt %	0.71
Carbon, wt %	84.86
Hydrogen, wt %	11.80
Oxygen, wt %	1.13

TABLE 4.15

Module: Modified In Situ (MIS) Retorts

(a) Equipment, facilities

Compressors
Pumps
Heat exchangers
Burners
Liquid-gas separation equipment
Oil-water separation equipment

(b) Assumptions

(1) Oil recovery is estimated to be approximately 60% of Fischer assay.
(2) Operation is 24 hours per day.
(3) Propane (at 90,962 Btu/gal) and diesel fuel (at 139,000 Btu/gal) are used to ignite the retorts.
(4) Product gas recovery is 2.447 x 10^9 scf per day (at 70 Btu/scf).
(5) Oil recovery is 50,000 barrels per day (at 6.0 x 10^6 Btu/bbl.)
(6) Weight of spent shale left in the retort is estimated at 100,000 tons of the 116,700 tons required to produce 50,000 BPD.

(c) Guidelines on data

(1) The data are for the production of 50,000 barrels of crude shale oil per day.
(2) Modification of the data to represent other production rates may be done by simple ratio.

(d) Data

(1) Direct energy for the production of 50,000 barrels of crude shale oil per day:

Electricity	766.2 x 10^6 kwh/yr	Ref. No. 4
Diesel fuel	121,000 gallsons/yr	Ref. No. 4
Propane	1.818 x 10^6 gal/yr	Ref. No. 4

(2) Materials requirements for production of 50,000 barrels of crude shale oil per day:

Total equipment energy (including initial construction, containing construction, and replacement)

634.4 x 10^9 Btu/yr	Ref. No. 4

TABLE 4.15

Continued

(3) Efficiency and Losses

- Oil recovery is estimated at 60% of Fischer assay.
- Overall efficiency is estimated at 73.4%.
- All power and fuel inputs are considered losses from the module.
- Principal energy losses and internal consumption are estimated at 170.6 x 10^9 Btu/day.

(e) Data sources

(1) Marland, G., 1977, Net energy analysis of in situ oil shale processing: Oak Ridge, Tennessee, Oak Ridge Associated Universities, 29 p.
(2) Griffis, R.L., and Baughman, G.L., 1981, Parameters affecting the characteristics of oil shale-derived fuels: Golden, Colorado, Colorado School of Mines Research Institute, 145 p.
(3) McDermott, W.F., 1981, Development of a commercial oil shale project: Paper presented at 6th IIASA Resources Conference, Colorado School of Mines, June 15-17.
(4) Cha, C.Y., and Garrett, D.E., 1975, Energy efficiency of the Garrett in situ oil shale process, in Quarterly of the Colorado School of Mines, vol. 70, no. 3: Golden, Colorado, Colorado School of Mines, p. 31-39.

Module Energy Summary:

(1) Principal Energy Input
Type: 30 gal/ton oil shale, rubbled
Quantity, units: 116,700 tons/day
Btu/unit: 2750 Btu/lb = 5.50 x 10^6 Btu/ton
Btu input: 641.9 x 10^9 Btu/day

(2) Principal Energy Loss
170.6 x 10^9 Btu/day

(3) Principal Energy Output
Type: Crude shale oil
Quantity: 50,000 BPD = 6.0 x 10^6 Btu/day
Type: Product gas
Quantity: 2.447 x 10^9 scf/day = 171.3 x 10^9 Btu/day

(4) Process Efficiency
73.4%

(5) Principal Energy to be used within Process Boundary
171.3 x 10^9 Btu/day

4.1.3.6 Multi Mineral Retorted

In order to recover several products from the Saline Zone resources of the Piceance Creek basin, the Multi Mineral Corporation has initiated a testing program to develop the "Integrated In Situ Process." This process would produce nahcolite, shale oil, fuel gas, alumina, and soda ash in one integrated operation. In general, the process integrates the multi-mineral technology with the modified in situ method.

For simplicity of description, the process can be considered as a three-step operation:

I Mining and Nahcolite Recovery
II Retorting and Hydrocarbon Recovery
III Leaching and Soda Ash-Alumina Recovery

Mining and Nahcolite Recovery. Access to the Saline Zone is through large diameter shafts. The process involves creating large underground stopes (chambers) filled with fragmented oil shale. In the Saline Zone, the column of rubble is nahcolite-bearing. Nahcolite is recovered from the oil shale by extracting the rubble from the stope through funnel-like openings at the base and feeding to an underground crushing-screening process. Nahcolite, being more brittle than oil shale, fragments in the crusher to smaller particles than does the oil shale. The nahcolite is recovered (about 80% purity) in the fine fraction from the screening process and is moved to the surface for market.

The top size from the screening process (+4"), essentially free of nahcolite, comprises about 65% of the total rock mined. This top size is backfilled into the stope simultaneously with extraction, as shown on Figure 4.12

Retorting. After backfilling, retorting of the shale is accomplished by gas-to-solids heat exchange in a "retort set" as shown on Figure 4.13. A retort set is three stopes simultaneously being processed--one for pyrolysis and oil production, one for gasification of the residual carbon which remains in the oil shale after pyrolysis, and one for recovery of the sensible heat from the hot retorted-gasified shale. The products formed, along with the pyrolysis water, are directed to a collection sump where the oil, water and gas are separated. The oil and excess gas are pumped to the surface for marketing; the gas used for pyrolysis is recycled and the water is used in the leaching step.

Leaching. During retorting of oil shale, dawsonite in the shale is decomposed into two compounds--soda ash (Na_2CO_3) and aluminum oxide (Al_2O_3). If the temperature and other conditions are properly controlled during retorting, the aluminum oxide formed will be soluble in a light basic liquor along with the soda ash. After the shale in the retort is cooled, the soda ash and aluminum can be leached by spraying water over the top of the retorted shale and collecting this water as pregnant liquor at the base. This can be done in more than one chamber simultaneously in a countercurrent process. The pregnant liquor is then pumped to the surface for recovery and marketing of the alumina and soda ash. The depleted liquor is recycled.

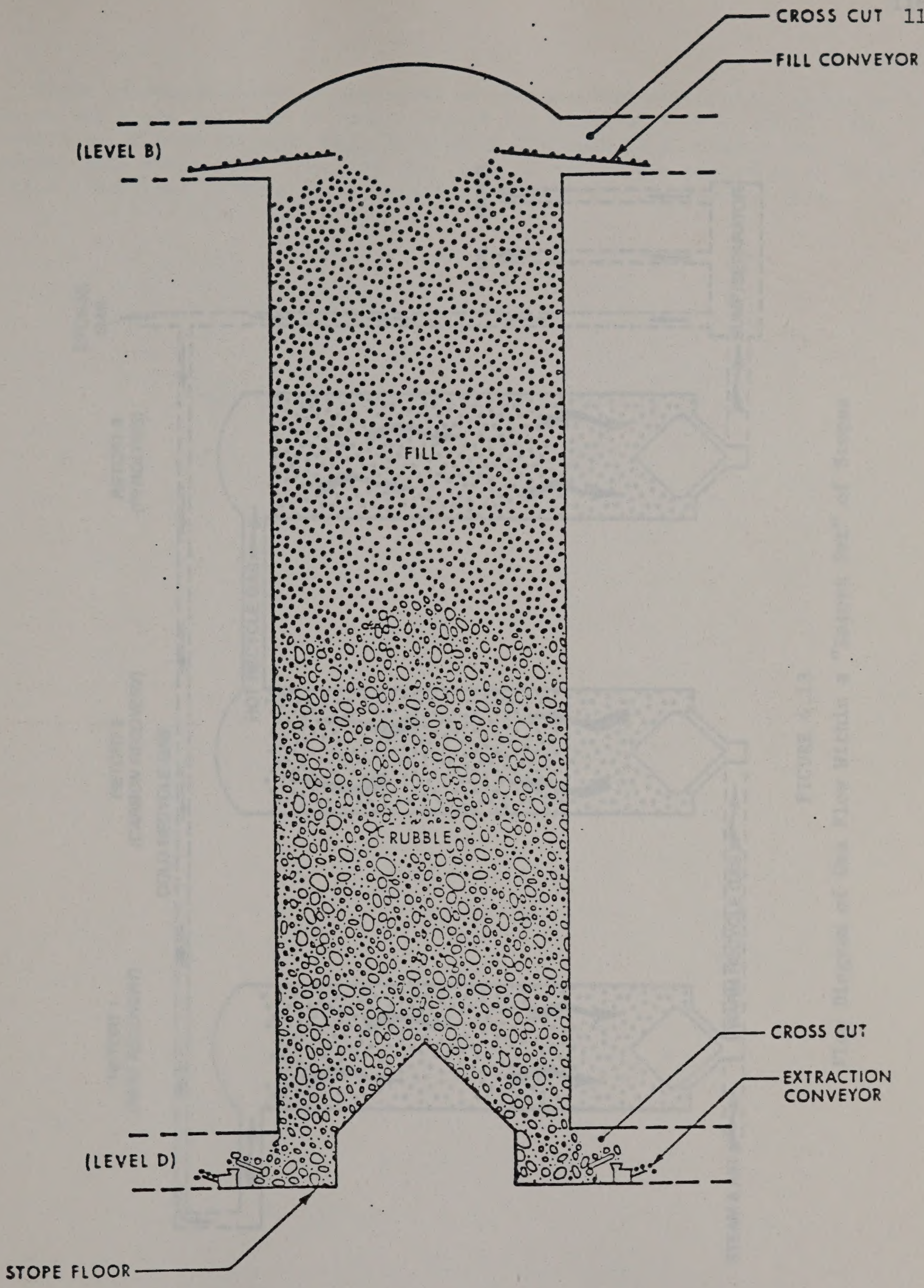


FIGURE 4.12

Diagram of Stope Showing Simultaneous Extraction and Backfilling Operations

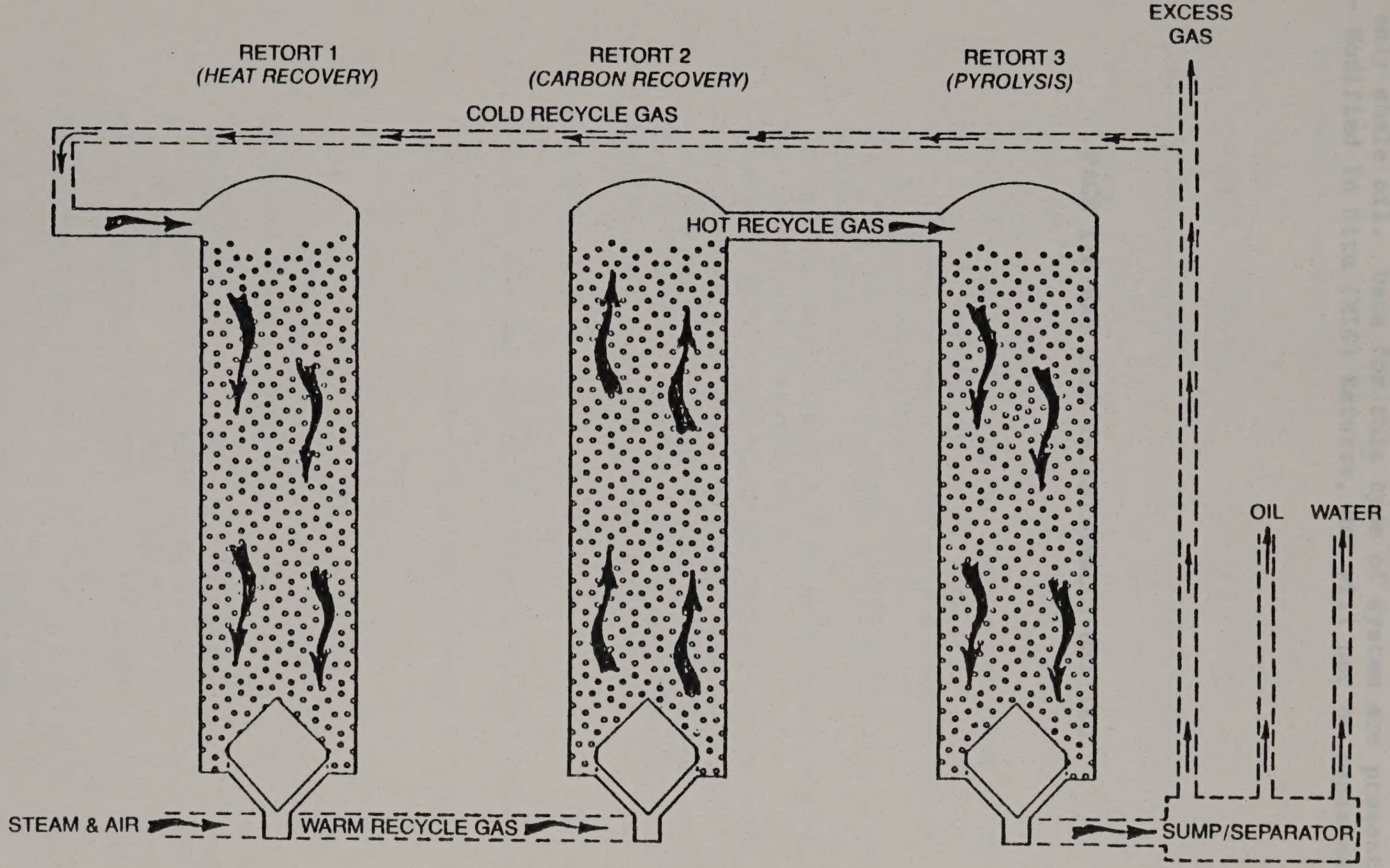


FIGURE 4.13

Flow Diagram of Gas Flow Within a "Retort Set" of Stopes

Since an adequate energy appraisal of the recovery of multiple products from an oil shale facility is vastly beyond the scope of this handbook, the "Integrated In Situ Process" will be treated the same as a process that produces only shale oil. Data for this type of system are presented in Section 4.1.3.4 - Modified In Situ (MIS) Retorts, and will not be repeated here.

PAGE 118 HAS BEEN INTENTIONALLY OMITTED.

TABLE 4.16

Module: True In Situ (TIS) Retorts

(a) Equipment, facilities

Drill rigs
Low pressure blowers
Pumps
Gas cleanup equipment

Explosives
Diesel fuel
Electricity

Recovery = 50%

(b) Assumptions

(1) Recovery of oil from the fractured shale within the retort boundaries in 50%.
(2) The shale is assumed to have a Fischer assay of 30 gallons/ton and a gross heating value of 5.50 x 10^6 Btu/ton.
(3) 98 x 10^6 scf of product gas with a heating value of 70 Btu/scf are produced each day.
(4) 2000 barrels of crude shale oil (6.0 x 10^6 Btu/bbl) are produced each day.
(5) Explosives requirements are in proportion to the requirements for MIS retort preparation.
(6) Materials requirements are approximately one-half of the requirements that would be called for by a simple ratio of the requirements for MIS retorting. This assumption seems valid in view of the fact that one of the primary objectives of the TIS technique is to minimize capital costs.

(c) Guidelines on data

(1) The data are for the production of 2,000 barrels of crude shale oil per day.
(2) The data can be scaled to other production rates by simple ratio.

(d) Data

(1) Direct energy and materials for the production of 2,000 barrels of crude shale oil per day:

Electricity	30.6 x 106 kwh/yr	Ref. No.	6
Diesel fuel	4840 gallons/yr	Ref. No.	4
Explosives	900 tons/yr	Ref. No.	5
Other materials	12.7 x 10^9 Btu/yr	Ref. No.	6

(3) Efficiency and Losses

- o Oil recovery is 50% of Fischer assay.
- o Overall efficiency is 61.2%.
- o Total principal energy losses are 11.94 x 10^9 Btu/day.

TABLE 4.16

Continued

(e) Data sources

(1) Lekas, M.A., 1981, The Geokinetics horizontal in situ retorting process, in Fourteenth Oil Shale Symposium Proceedings: Golden, Colorado, Colorado School of Mines, p. 146-153.
(2) Lekas, M.A., 1979, Progress report on the Geokinetics horizontal in situ process, in Twelfth Oil Shale Symposium Proceedings: Golden, Colorado, Colorado School of Mines, p. 228-236.
(3) TRW Energy Systems Group, 1979, Oil shale data book: McLean, Virginia, TRW Energy Systems Group, 439 p.
(4) Marland, G., 1977, Net energy analysis of in situ oil shale processing: Oak Ridge Associated Universities, February.
(5) Ash, J.L., Stone, R.B., Craig, W.E., and Engler, M.R., 1976, Technical and economic study of the modified in situ process for oil shale: Tulsa, Oklahoma, Fenix & Scisson, Inc., 344 p.
(6) Cha, C.Y., and Garrett, D.E., 1975, Energy efficiency of the Garrett in situ oil shale process, in Quarterly of the Colorado School of Mines, vol. 70, no. 3: Golden, Colorado, Colorado School of Mines, p. 31-39.

Module Energy Summary:

(1) Principal Energy Input
Type: 30 gal/ton oil shale, fractured
Quantity, units: 5,600 tons/day
Btu/unit: 5.50 x 10^6 Btu/ton
Btu input: 30.80 x 10^9 Btu/day

(2) Principal Energy Loss
11.94 x 10^9 Btu/day

(3) Principal Energy Output
Type: Crude shale oil
Quantity: 2,000 BPD = 12.00 x 10^9 Btu/day
Type: Product gas
Quantity: 98 x 10^6 scf/day = 6.86 x 10^9 Btu/day

(4) Process Efficiency
61.2%

(5) Principal Energy to be used within Process Boundary
6.86 x 10^9 Btu/day

4.1.4 Shale Disposal

After retorting the shale to recover the oil, the oil shale developer is faced with the problem of disposing of the spent shale that remains. This problem may be dealt with by disposing of the spent shale either above ground or underground.

Surface disposal of spent shale involves several steps. The shale must be transported to the disposal site, wetted somewhat to aid in compaction and to control dust, compacted to provide strength and to reduce permeability, and, finally, the shale must be graded and revegetated. Grading and revegetation efforts are aimed at restoring, as much as possible, the aesthetic appeal of the disposal site and matching it to the topography and vegetation of the surrounding area. Most developers intend to cover the spent shale with topsoil before planting to encourage plant growth and to make the disposal sites blend more readily into the surrounding terrain.

Underground disposal follows basically the same procedure except that grading and revegetation can be eliminated. In general, underground disposal is utilized when the raw shale has been obtained by underground mining methods and a cavern has been created in which the spent shale can be disposed.

A third technique that applies to MIS retorts uses the shale that is mined to create void space in the retort. Assuming that the mined shale is retorted using an appropriate surface technology, that spent shale can then be used to prepare a slurry that is injected into the burned out MIS retort. This technique is designed to (1) minimize the amount of spent shale that must be disposed of on the surface, (2) strengthen the burned out MIS retort to minimize subsidence, and (3) render the burned out MIS retort impermeable, thereby avoiding the contamination of underground aquifers that would otherwise flow through the retorts and leach soluble salts and other substances from the spent shale. This technique is in the very early stages of development and worthwhile data concerning its energy requirements are not yet available.

Module Elements and Data

This module consists of two elements: (1) hauling and compacting and (2) revegetation. Since the options of surface and underground disposal are essentially the same with the exception of the revegetation element, only one set of data is presented for each element. The handbook user should be aware that, for surface disposal, the energy and materials requirements of the two elements must be added to determine the total energy and materials requirements of the module. For underground disposal, the energy and materials requirements for the hauling and compacting element only should be used to determine the total module requirements. Table 4.17 presents the data and assumptions for this module.

TABLE 4.17

Module: Shale Disposal

Element 1: Hauling and Compacting

(a) Equipment, facilities:

Conveyors
Dump trucks
Compactors
Bulldozers

(b) Assumptions:

(1) Haulage to the disposal site is by diesel-powered dump trucks.
(2) Approximately 6,000 gallons of water are required to moisten 1000 tons of spent shale.
(3) Operation is 24 hours per day, 365 days per year.

(c) Guidelines on data

(1) Data are for the disposal of 1000 tons of spent shale.
(2) Scaling to different disposal tonnages can be done using a simple ratio.

(d) Data

(1) Direct energy for hauling and compacting 1000 tons of spent shale:

Diesel fuel	70 gal/1000 tons	Ref. No. 5
Lubricating oil	2.7 gal/1000 tons	Ref. No. 5

(2) Materials requirements for hauling and compacting 1000 tons of spent shale:

Steel	19.3 lbs/1000 tons	Ref. No. 5
Rubber	3.3 lbs/1000 tons	Ref. No. 5

(3) Efficiency and Losses

- All fuel and oil consumed during hauling and compacting are considered losses from the module.
- All energy associated with the spent shale itself is considered a loss from the module.

TABLE 4.17

Continued

(e) Data sources

(1) Holtz, W.G., 1976, Disposal of retorted oil shale from the Paraho oil shale project: Grand Junction, Colorado, Development Engineering, Inc., 471 p.
(2) TRW Energy Systems Group, 1979, Oil shale data book: McLean, Virginia, TRW Energy Systems Group, 439 p.
(3) Earnest, H.W., Rajaram, V., Kauppila, T.A., and Hill, J.R.M., 1977, Underground disposal of retorted oil shale, in Tenth Oil Shale Symposium Proceedings: Golden, Colorado, Colorado School of Mines, p. 213-222.
(4) Melcher, A.G., and others, 1976, Net energy analysis - An energy balance study of fossil fuel resources: Golden, Colorado, The Colorado Energy Research Institute, 218 p.
(5) Private communication with a major engineering company.

Element 2: Revegetation

(a) Equipment, facilities

Water trucks
Light duty trucks

(b) Assumptions:

(1) A layer of topsoil is spread over the top of the spent shale before re-planting efforts are begun.
(2) The data represent energy and materials requirements for revegetating each 1000 tons of spent shale.

(c) Guidelines on data

(1) See Assumption #2 above.
(2) Scaling to different spent shale disposal rates may be done by simple ratio.

(d) Data

(1) Direct energy requirements for revegetating 1000 tons of spent shale:

Gasoline	0.28 gal/1000 tons	Ref. No. 5
Lubricating oil	0.0025 gal/1000 tons	Ref. No. 5
Electricity	12.5 kwh/1000 tons	Ref. No. 5

TABLE 4.17

Continued

(2) Materials requirements for revegetating 1000 tons of spent shale:

Equipment steel	0.37 lbs/1000 tons	Ref. No. 5
Rubber	0.023 lbs/1000 tons	Ref. No. 5
Copper	0.019 lbs/1000 tons	Ref. No. 5

(3) Efficiency and Losses

- All energy consumption is considered a loss from the module.

(e) Data sources

(1) Holtz, W.G., 1976, Disposal of retorted oil shale from the Paraho oil shale project: Grand Junction, Colorado, Development Engineering, Inc., 471 p.

(2) TRW Energy Systems Group, 1979, Oil shale data book: McLean, Virginia, TRW Energy Systems Group, 439 p.

(3) Earnest, H.W., Rajaram, V., Kauppila, T.A., and Hill, J.R.M., 1977, Underground disposal of retorted oil shale, in Tenth Oil Shale Symposium Proceedings: Golden, Colorado, Colorado School of Mines, p. 213-222.

(4) Melcher, A.G., and others, 1976, Net energy analysis - An energy balance study of fossil fuel resources: Golden, Colorado, The Colorado Energy Research Institute, 218 p.

(5) Private communication with a major engineering company.

Module Energy Summary

(1) Principal Energy Input
Type: Retorted shale
Quantity, Units: based on output from retort
Btu/unit: based on output from retort
Btu/input: based on output from retort

(2) Principal Energy Loss
100% of any energy in input stream

(3) Principal Energy Output
None

(4) Process Efficiency
Varies with ratio of item (5) to item (1)

(5) Principal Energy to be used within Process Boundary
None normally, but use is conceivable

4.1.5 Shale Oil Upgrading

Discussion of Process

Raw shale oil from a retorting process resembles conventional crude petroleum in many respects. However, some of its properties make raw shale oil more difficult to transport in a pipeline and much more difficult to process in a refinery. The properties that make shale oil more difficult to transport are its high pour point (the lowest temperature at which it will pour; i.e., remain a liquid) and its high viscosity (a measure of its resistance to flow). The properties that make it difficult to process in a refinery are its high concentrations of nitrogen, iron, and arsenic which destroy (poison) the catalysts used in refinery processes. Table 4.18 summarizes the more significant differences between raw shale oil and conventional crude petroleum.

Because crude shale oil presents some unusual problems, many developers are planning to upgrade the oil to a more compatible synthetic crude. Many different upgrading schemes have been proposed that vary in the severity of the processing steps and operating conditions. The mild upgrading processes merely make the shale oil more suitable for pipeline transport. The moderate processes make the raw shale oil suitable as a refinery feedstock or a boiler fuel. The severe upgrading processes make the oil into a premium refinery feedstock.

Shale oil upgrading is treated as a single module with one element in this handbook. The module is for a severe upgrading process that incorporates a distillation column, a coker, a hydrotreater, a hydrogen plant, and a gas cleanup facility.

Many different processes can be used to upgrade raw shale oil and these processes can be combined in a wide variety of combinations. Additionally, the operating conditions of most processes can be changed to provide a broad range of severity. Hence, an almost infinite number of potential upgrading schemes can be devised.

Visbreaking is a mild thermal process that involves heating the oil to 900° to 1000°F for from several seconds to several minutes. The larger molecules in the oil are broken into smaller molecules, thus reducing the pour point and (normally) the viscosity of the oil. Visbreaking, however, has little or no effect on the concentrations of nitrogen, iron, or arsenic.

Coking is a slightly more severe thermal process that produces smaller molecules (both liquids and gases) and a solid residue called coke. Variations on the basic process include delayed coking, fluid coking, and flexicoking. Coking reduces the pour point and viscosity of the product liquid (referred to as coker distillate). The nitrogen, iron, and arsenic tend to concentrate in the coke, thus tending to somewhat improve the quality of the liquid coker distillate.

Heavy oil cracking is very similar to coking in that it produces coke and a distillate containing smaller molecules. However, with heavy oil cracking, the coke is then burned to produce steam. The treated oil is then contacted with hydrogen to produce a product similar to coker distillate.

TABLE 4.18

Properties of Raw Shale Oil and Conventional Crude Petroleum

PROPERTIES	RAW SHALE OIL	CONVENTIONAL CRUDES
Pour Point, °F	60 to 90	less than 15
Nitrogen, wt %	1.3 to 2.2	0.01 to 0.65
Arsenic, ppm	20 to 50	0.0 to 0.03
Iron, ppm	50 to 100	1.0 to 70
Sulfur, wt %	0.6 to 0.9	0.04 to 4.0

Hydrotreating involves contacting the raw shale oil with hydrogen in the presence of a catalyst at high temperatures and pressures. In the process, the larger molecules are broken into smaller ones, the nitrogen is converted to ammonia, and the sulfur is converted to hydrogen sulfide (H_2S). Both the ammonia and the H_2S can then be easily removed from the oil. The arsenic and iron are converted to compounds that can be removed by contact with an inert material referred to as a guard bed. Hydrotreating can accomplish varying degrees of upgrading by the severity of the operating conditions. More severe conditions are defined as higher pressures, higher temperatures, longer contact time with the catalyst, higher catalyst consumption, and higher hydrogen consumption.

Distillation is a process that is incorporated into nearly all upgrading schemes (although it is often not explicitly stated as an upgrading process) to separate a process stream into several streams (fractions) according to boiling point. The components in the feed stream that boil at high temperatures pass out the bottom of the distillation column while the components that boil at low temperatures pass out the top. Often, several other streams are also removed from intermediate points in the distillation column. The feed to a distillation column can be the entire raw shale oil and/or it can be an intermediate stream from another processing unit (such as coker distillate, for example).

Other processes that are not as widely suggested for shale oil upgrading include catalytic cracking, hydrocracking, and catalytic reforming. These processes are, however, potentially visable in certain upgrading schemes.

Module Elements and Data

Shale oil upgrading could be conceivably subdivided into several elements. However, net energy data is generally not available for each individual process, but rather it is presented for an entire facility comprised of several processes. Therefore, this handbook presents an upgrading scheme as one module with one element. The upgrading scheme selected is comprised of a distillation column, a coker, a hydrotreater, a hydrogen manufacturing plant, and a gas cleanup facility. The primary product of the process is 50,000 bpd of upgraded shale oil that will be used as a premium refinery feedstock. Additionally, coke, ammonia, and sulfur are produced as by-products and are sold. This upgrading process is presented schematically in Figure 4.14.

The upgrading process selected for analysis consists of first distilling the raw shale oil from the retorts into two liquid streams. The low-boiling components pass out the top of the where the gases are separated for further processing and the liquids are sent to a hydrotreater. The high-boiling components primarily larger molecules in the shale oil pass out the bottom of the distillation column and are sent to a coker. From the coker, the distillate (liquids) are sent to the hydrotreater, the gases are sent to the gas cleanup plant, and the coke is stockpiled and sold. The liquids from the top of the distillation column and from the coker are hydrotreated to produce 50,000 bpd of a high-quality refinery feedstock. Gases from the hydrotreater are combined with the other two gas streams (from the distillation column and

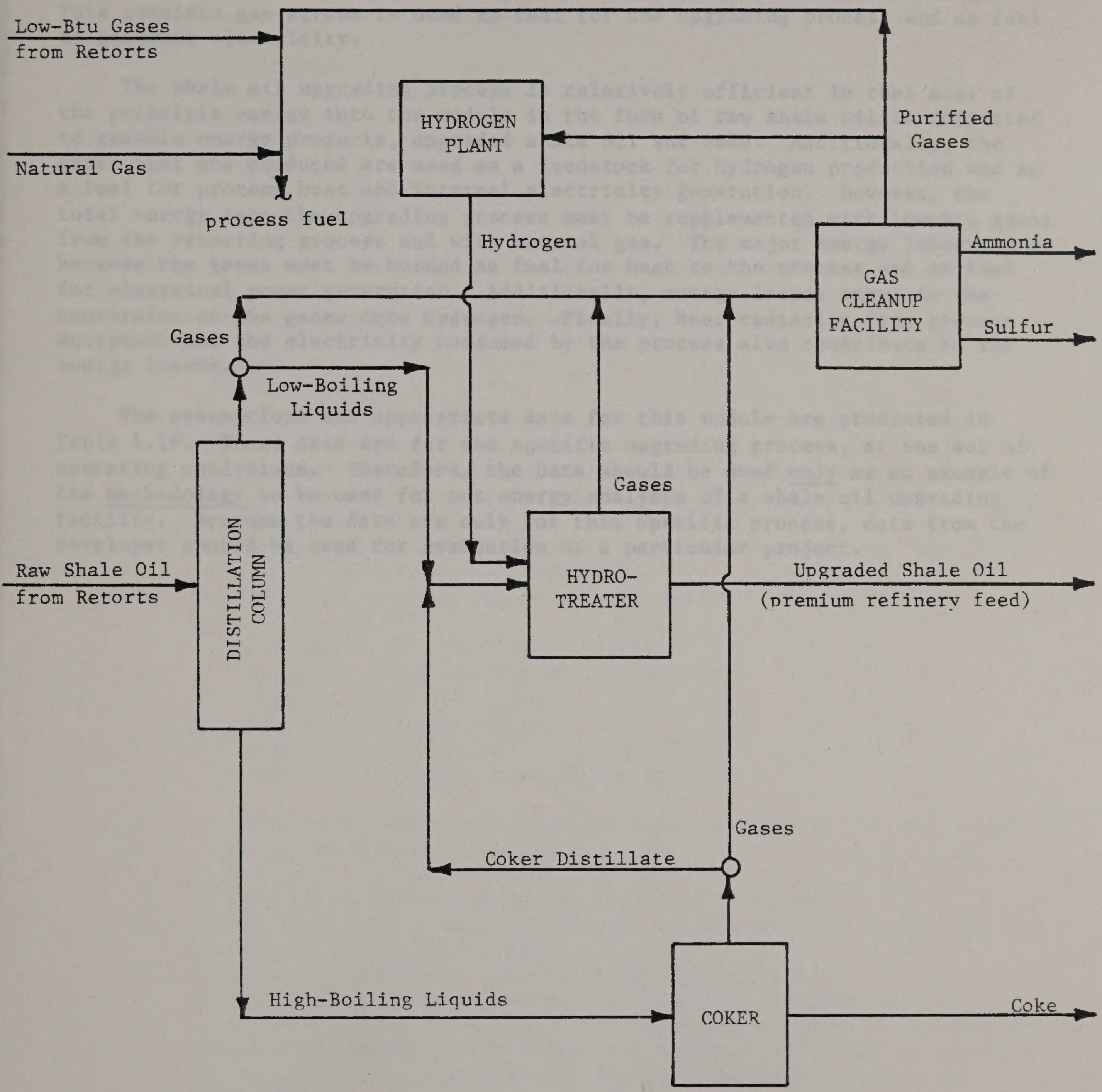


FIGURE 4.14

Schematic of a Shale Oil Upgrading Facility

the coker) and they are then cleansed by contact with water. The water, which now contains hydrogen sulfide (H_2S) and ammonia, is first heated to remove the H_2S and then heated further to remove the ammonia (which is sold as a by-product). A Claus sulfur plant is used to convert the H_2S into sulfur which is also sold as a by-product. Part of the cleansed gases are used to produce hydrogen for the hydrotreating process. The remainder of the gases are combined with low-Btu gases from the retorting process and with natural gas. This combined gas stream is used as fuel for the upgrading process and as fuel to generate electricity.

The shale oil upgrading process is relatively efficient in that most of the principle energy into the module in the form of raw shale oil is converted to useable energy products, upgraded shale oil and coke. Additionally, the gases that are produced are used as a feedstock for hydrogen production and as a fuel for process heat and internal electricity generation. However, the total energy into the upgrading process must be supplemented with low-Btu gases from the retorting process and with natural gas. The major energy losses occur because the gases must be burned as fuel for heat to the process and as fuel for electrical power generation. Additionally, energy losses occur in the conversion of the gases into hydrogen. Finally, heat radiation from process equipment and the electricity consumed by the process also contribute to the energy losses.

The assumptions and appropriate data for this module are presented in Table 4.19. These data are for one specific upgrading process, at one set of operating conditions. Therefore, the data should be used only as an example of the methodology to be used for net energy analysis of a shale oil upgrading facility. Because the data are only for this specific process, data from the developer should be used for evaluation of a particular project.

TABLE 4.19

Module: Shale Oil Upgrading to a High-Quality Refinery Feedstock

(a) Equipment, facilities:

The primary process operations are:

Distillation
Coking
Hydrotreating
Hydrogen manufacture
Gas cleanup
Electrical power generation
Buildings

These operations are comprised of many components including vessels, furnaces, heat exchangers, pumps, motors, piping, valves, compressors, structural steel concrete, instrumentation, and many others.

(b) Assumptions:

(1) Energy usage is based on the specified upgrading scheme producing 50,000 bpd of premium refinery feedstock.
(2) The raw shale oil is assumed to be from a directly-heated retort that also produces excess low-Btu gases that can be used as fuel for the upgrading process.
(3) The low-Btu gases from the retort were assumed to retort have been treated to remove sulfur compounds.
(4) The following heating values were assumed:

raw shale oil = 6,000,000 Btu/bbl*
upgraded shale oil = 5,800,000 Btu/bbl*
natural gas = 994 Btu/scf
retort gas = 100 Bktu/scf
coke = 12,500 Btu/lb
ammonia and sulfur have no energy value

*these values were determined from several sources and confirmed in the Colony Project EIS

(5) No economies or diseconomies of scale were assumed.
(6) Electricity requirements are assumed to be completely satisfied by generation within the module.
(7) Materials requirements were estimated from values for oil shale retorting facilities requiring approximately the same capital investment of $104 MM (1973). The upgrading investment includes an apportional amount for utilities and services that will be common to the entire oil shale facility including mining, retorting, and upgrading.
(8) 331 operating days per year.

TABLE 4.19

Continued

(c) Guidelines on data:

(1) Data is only for the upgrading scheme to produce a high-quality refinery feedstock as illustrated in Figure 4.1.5b.

(2) Energy data may be multiplied by a linear factor based on barrels per day of upgraded shale oil produced relative to 50,000 bpd.

(d) Data:

(1) Direct Energy per 50,000 bpd of upgraded product:

Natural gas = 1.8×10^9 Btu/day
Low-Btu gases from the retorting facility = 51.2×10^9 Btu/day

(2) Materials:

Detailed information on the materials used are not available. It will be assumed that upgrading and refining modules are identical in materials inputs per unit output. It will be assumed also that, from reference (1) below, 1.31 Btu of materials energy is required for every 1000 Btu of refinery or upgrading plant output. Further, it will be assumed that the split of materials into various materials types is exactly the same as that of a direct heated retort (module 4.1.3.1). Therefore, the following materials consumption data apply. Note that these data are annual, and do not need to be adjusted for life of plant.

			Fuel: Btu for 50,000 ppd output Material		
Material	Crude Oil	Natural Gas	Coal	Hydro	Nuclear
Lumber	8.43×10^6	25.20×10^3	0	0	0
Str. Steel	16.69×10^9	25.60×10^9	72.54×10^9	505×10^6	3.86×10^9
Concrete	22.40×10^9	5.34×10^9	10.94×10^9	322×10^6	2.37×10^9
Stl. Equip.	47.27×10^9	72.96×10^9	209.90×10^9	1.55×10^9	11.34×10^9

(3) Losses:

Very little of the primary energy is lost in this module. The losses occur due to the use of gases from the process as fuel to provide heat and to generate electricity.

(e) Data Sources:

(1) Frabetti, Alton J., Jr., et. al., 1975, A study to develop energy estimates of merit for selected fuel technologies: East Sandwich, Mass., Development Sciences, Inc., 376 p.

(2) Katell, Signey, Stone, Reid, and Wellman, Paul, 1974, Oil shale - a clean energy source in Gary, James H., ed., Proceedings of the seventh oil shale symposium: Golden, CO, Colorado School of Mines, p. 1-20.

TABLE 4.19

Continued

Module Energy Summary

(1) Principal Energy Input
Type: Raw shale oil
Quantity, units: 52,350 bbl/day
Btu/unit: 6.0×10^6 Btu/bbl
Btu input: 314.1×10^9 Btu/day

(2) Principal Energy Loss
2.7×10^9 Btu/day

(3) Principal Energy Output
Type: upgraded shale oil) Coke
Quantity: 290.0×10^9 Btu/day) 21.4×10^9 Btu/day
) (1.712×10^6 lb/day
) at 12,500 Btu/lb)

(4) Process Efficiency
99.1%

(5) Principal Energy to be used within Process Boundary
Assumed to be none, but coke is available.

4.1.6 Shale Oil Transportation

Discussion of Process

Possible modes of transportation of shale oil or upgraded shale oil include pipeline, rail and truck. Barge and ship transport are not feasible.

For transporting raw shale oil, some questions are raised by the pipeline companies. For the most part, the crudes that the pipeline companies are now transporting are faily compatible. That is, even when a shipment of "good" crude that must be mixed with "bad" crude at the interface to preserve the quality of the "good" crude is not very great. Because of the high arsenic content of raw shale oil, pipeline companies are very concerned that once a shipment of raw shale oil passes through the pipeline, enough arsenic would plate out on the pipe walls that tremendous quantities of "good" conventional crude that followed would be adversely affected. The fact that arsenic plates out is well known, but the extend to which it would occur with raw shale oil, or the extent to which it would affect other oil, is not known. In fact, no real testing has been conducted to determine the extent of the problem. In view of the concern on the part of pipeline companies, transport of raw shale oil via existing pipelines may not be feasible. If it is done, the high viscosity of raw crude shale oil will result in about a 10% cost and pumping penalty compared to hydrotreated shale oil or natural crude. On the other hand, transport of hydro-treated shale oil in existing pipelines is apparently fully feasible.

For the transportation of large quantities of liquids between two points separated by great distances, railroads cannot economically compete with existing pipelines. However, railroads do offer many benefits not achievable with a pipeline. The first of these is flexibility--railroads can transport liquids as well as solids and even gases. Thus, once a rail line is installed, it may serve to transport shale oil as well as equipment, chemicals, byproducts, and a variety of other materials to and from a plant site. Secondly, given the immense network of rail lines, it is possible to get almost any commodity, including shale oil, between any two sites in the country. Furthermore, the material to be shipped, being in relatively discrete segments in the cars, may be distributed fairly easily to any number of different sites. Because of this flexibility, railroads can be a very advantageous way to transport goods having several discrete markets which may change periodically. Such could be the case with the marketing of shale oil (either raw or upgraded) as a boiler fuel or as a refinery feedstock to several smaller independent refineries.

Trucks represent a potentially viable transportation method for the transport of relatively small quantities of liquids over short to medium distances. In this study, truck transport is considered for shipment of both raw shale oil and hydrotreated shale oil. The shipment of 15,000 bpd of shale oil would require a minimum of 98 trucks/day leaving a plant site; this is one truck every 15 min. Including the return trip, this means nearly 200 one-way trips between the plant site and the terminal every day. Shipment of 50,000 bpd would require 327 trucks per day or one every 4-1/2 min. These figures assume about 153 Bbl. per truck.

Elements and Data

Each mode of transportation is treated as a separate table in this section. Elements, assumptions and data are presented for each module.

TABLE 4.20

Module: Shale Oil Transportation: Pipeline

(a) Equipment, facilities:

Pipe
Pumps, motors
Concrete, structural steel
Contract construction: excavation, pipelaying, etc.

(b) Assumptions:

(1) Data ore for 100 miles of pipeline, per 1 x 10^9 Btu (166.5 Bbl) moved; linear scaling for both quantity and distance is assumed.
(2) Pipeline head loss is assumed to be 10 psi/mile.

(c) Guidelines on data

(1) Multiply data by ratio of actual length in 100 miles to assumed length of 100 miles; i.e., for 200-mile pipeline, multiply by 2.
(2) Multiple given data by ratio of actual Btu transported to assumed 1 x 10^9 Btu transported.

(d) Data:

(1) Direct energy for transport of 1 x 10^9 Btu of shale oil in a 100-mile pipeline:

Electricity	26,880 Kwh/year	Ref. No. 3

(2) Materials requirements for transport of 1 x 10^9 Btu of shale oil in a 100-mile pipeline:

Steel	20,550 tons/100 miles	Ref. No. 3
Concrete	16,060 tons/100 miles	Ref. No. 3

(3) Efficiency and Losses
- Barring the possibility of a major spill or pipeline leak, there are no principal energy losses from the pipeline transportation module.
- All electricity required by the pipeline system is considered a loss from the module.

(e) Data sources:

(1) TRW Energy Systems Group, 1979, Oil shale data bank: McLean, Virginia, TRW Energy Systems Group, 439 p.
(2) Considine, D.M. (editor), 1977, Energy Technology Handbook: New York, NY, McGraw Hill, Inc. 1957 p.
(3) Private communications with major engineering companies.

TABLE 4.20

Continued

Module Energy Summary

(1) Principal Energy Input
Type: Shale oil (crude or upgraded)
Quantity, units: 166.5 barrels
Btu/unit: 6.006×10^6 Btu/bbl
Btu input: 1.00×10^9 Btu

(2) Principal Energy Loss
None

(3) Principal Energy Output
Type: Shale oil (crude or upgraded)
Quantity: 166.5 barrels = 1.00×10^9 Btu

(4) Process Efficiency
100%

(5) Principal Energy to be used within Process Boundary
None

TABLE 4.21

Module: Shale Oil Transportation: Rail

(a) Equipment, facilities:

Track
Diesel engines
Tank cars, assume 22,860 gallons per car times 7.4 lb/gallon = 169,200 lbs. payload per car.
Loading and unloading pumps, pipes, tank farms.
Construction equipment for roadbed construction and rail-laying.

(b) Assumptions:

(1) Btu of energy and materials inputs per ton-mile are the same as those for a unit coal train.
(2) The density of shale oil is approximately 315.3 lb/bbl.

(c) Guidelines on data:

(1) Energy assumption is presented based on the transportation of 1000 tons (6343 bbls) of shale oil for one mile. The figure must be multiplied by the number of miles (round trip) that the train travels and also by thousands of tons of shale oil transported.
(2) Materials requirements shown are for the life of the project, assumed to be 35 years. The data are presented on a per mile basis and must be multiplied by the number of miles of railway that are constructed. Steel in train is for a single train capable of transporting 50,000 barrels of shale oil.

The weight of a train of tank cars is estimated at 3266 tons. The number of trains is a function of the time required to load the train, travel to the destination, unload, and return to the loading point. For this project, it is assumed that the loading and unloading facilities can handle 10 cars simultaneously, each at 363 Bbl/hr, or 3630 Bbl total per hour per train. An average speed of 40 mph is also assumed. For a 50,000 Bbl/day module, the number of trains would be:

$$\text{Number of trains} = \left(\frac{50{,}000\ \text{BBl}}{\text{day}}\right)\left(\frac{\text{day}}{24\ \text{hrs}}\right)\left(\frac{\text{trains}}{50{,}000\ \text{Bbl}}\right)\left(\frac{\text{hours}}{\text{cycle}}\right)$$

$$\text{cycle time} = 2\left(\frac{50{,}000\ \text{Bbl}}{3630\ \text{Bbl/hr}}\right) + \frac{\text{miles}}{40\ \text{miles/hr}}$$

$$\text{Number of trains} = 0.0833\left(13.8 + \frac{\text{miles}}{40}\right)$$

$$\text{Annual weight of trains} = \frac{3266\ \text{tons}}{35\ \text{years}}(0.0833)\left(13.8 + \frac{\text{miles}}{40}\right)$$

$$= 7.77\left(13.8 + \frac{\text{miles}}{40}\right)$$

TABLE 4.21

(Continued)

(d) Data:

(1) Direct energy per 1000 tons/mile of shale oil transported:

Diesel Fuel	2.5 gallons/1000 ton/miles	Ref. No. 1

(2) Materials requirements for rail transport of shale oil

Steel in track	288 ton/mile	Ref. No. 1
Rock (ballast)	2762 ton/mile	Ref. No. 1
Wood (ties)	355 ton/mile	Ref. No. 1
Steel in train	$7.77\left(13.8 + \frac{\text{miles}}{40}\right)$tons	Discussion: Ref. No. 1

(3) Efficiency and Losses

- There are no principal energy losses from the rail transport module.
- All fuel consumed by the train is considered a loss from the module.

(e) Data sources:

(1) Private communications with major engineering companies.

Module Energy Summary

(1) Principal Energy Input
Type: Shale oil (crude or upgraded)
Quantity, units: 50,000 bbl/day
Btu/unit: 6.006×10^6 Btu/bbl
Btu input: 300.3×10^9 Btu/day

(2) Principal Energy Loss
None

(3) Principal Energy Output
Type: Shale oil (crude or upgraded)
Quantity: 50,000 BPD = 300.3×10^9 Btu/day

(4) Process Efficiency
100%

(5) Principal Energy to be used within Process Boundary
None

TABLE 4.22

Module: Shale Oil Transportation: Truck

(a) Equipment, facilities:

Tractors
Trailers
Loading facilities (pumps, tanks, piping)

(b) Assumptions:

(1) Truck haulage is a viable option for transporting 15,000 barrels of shale oil per day, or less.
(2) Maximum haul distance is assumed to be 100 mi, one way
(3) Average speed on the road is 40 mph.
(4) Each trailer can carry 50,000 lbs (154 bbls) of shale oil.
(5) Diesel fuel mileage is 5 mi/gal.

(c) Guidelines on data:

(1) The data are for transporting 15,000 barrels of shale oil per day over a one-way distance of 100 miles (200 miles round trip). Data may be scaled by multiplying by the factor

$$\frac{\text{actual production}}{15{,}000} \times \frac{\text{R.T. distance}}{200}$$

(2) Materials requirements are presented for both initial acquisition and maintenance.

(d) Data:

(1) Direct energy for transporting 15,000 barrels of shale oil per day a distance of 100 miles (one-way):

Diesel fuel	3900 gallons/day	Ref. No. 1

(2) Materials requirements for transporting 15,000 barrels of crude shale oil per day:

Initial

Steel	370 tons	Ref. No. 1
Aluminium	123 tons	Ref. No. 1
Rubber	32 tons	Ref. No. 1

Maintenance

Steel	9 tons/year	Ref. No. 1
Rubber	32 tons/year	Ref. No. 1

(3) Efficiency and Losses

- There are no principal energy losses for this module.
- All fuel consumption is considered a loss from the module.

TABLE 4.22

(Continued)

(e) Data sources:

(1) Private communications with major engineering companies.

Module Energy Summary

(1) Principal Energy Input
Type: Shale oil (crude or upgraded)
Quantity, units: 15,000 bbl/day
Btu/unit: 6.006×10^6 Btu/bbl
Btu input: 90.09×10^9 Btu/day

(2) Principal Energy Loss
None

(3) Principal Energy Output
Type: Shale oil (crude or upgraded)
Quantity: 15,000 BPD = 90.09×10^9 Btu/day

(4) Process Efficiency
100%

(5) Principal Energy to be used within Process Boundary
None

4.2 RELATED MODULE AND GENERAL MODULE COEFFICIENTS

This section contains one module which may be introduced into an oil shale trajectory: the water delivery module. The section also contains the coefficients and data for use in all modules, to determine:

(1) indirect energy, item (8) on the module analysis worksheet

(2) materials energy, item (9) on the module analysis worksheet

(3) infrastructure energy.

Also, conversion factors in general (gallons of oil to Btu's, gallons per ton assay of shale oil to Btu/ton, etc.) are presented.

4.2.1 Water Delivery

An area of primary importance to any energy development project is that of water acquisition and delivery. There are a number of options by which water may be obtained and transported. For the sake of simplicity, only one portion will be examined in this handbook. The applicability of this option to specific projects may be determined by communicating with project personnel and the module can be modified accordingly.

Water is extracted from a river or other source through a system of collector wells located adjacent to the source. Each collector well is equipped with a pump to draw out the water. The water would be delivered to a 36-inch pipeline that would transport the water to the project site. An initial pump station and a booster station are required to maintain proper line pressure for delivery of 30 cubic feet per second (cfs) of water.

Module Elements and Data

The water delivery module consists of one element: the water collection and delivery system. The distinct absence of disaggregated data makes it necessary to include both operations in a single element. Table 4.23 presents data and assumption for the module.

TABLE 4.23

Module: Water Delivery

(a) Equipment, facilities

Pumps
Pipe
Protective buildings

(b) Assumptions

(1) The pipeline delivers water at a flow of 30 cfs.
(2) The pipeline is 18 miles long, nominal diameter is 36 inches.
(3) The pipeline operates 24 hours per day, 331 days per year.

(c) Guidelines on data

(1) The data are for delivery of water at a rate of 30 cfs in the pipeline system.
(2) Because of the procedures involved with pipeline design, it is not advised that these data be scaled to other water delivery rates. Instead, new data should be acquired for the project developer.

(d) Data

(1) Direct energy for delivery of water at 30 cfs:

Electricity	33.93×10^6 kwh/yr	Ref. No. 1

(2) Materials requirements for delivery of water at 30 cfs.

Steel	4566 tons	Ref. No. 1
Concrete	3566 tons	Ref. No. 1

(3) Efficiency and losses

- Electricity requirements are considered as a system loss.
- No material (water) losses are expected.

(e) Data sources

(1) Private communications with a major engineering company.

Module Energy Summary

Not appropriate for this module

4.2.2 Indirect Energy

Indirect energy as resources in the ground, by type of resource, is calculated by using the trajectories for energy production from the 1976 Colorado Energy Research Institute study on net energy. Those trajectories yield direct energy and include all the indirect energy and energy in materials, traced back to resources in the ground. The major adjustment which is made is to adjust the electricity fuel or generation mix from the U.S. average used in the CERI study to the generation mix which is typical of the oil shale region.

The indirect energy is expressed in this handbook as coefficients to be used for multiplying the direct energy data. These multipliers are given in Table 4.24. To illustrate, from table 4.24, it can be seen that, for a direct energy input of 1 kwh (3413 Btu) of electricity, the resources in the ground which are required are 5150 Btu of coal, 245 Btu of crude oil, 4740 Btu of natural gas, 590 Btu of hydropower, and no nuclear energy.

This approach has slight inaccuracies, and the data do not reflect possible improvements in industrial energy efficiency or resource recovery efficiency. To illustrate the latter approach, the petroleum resources in the ground are currently recovered with about a 0.31% efficiency; enhanced oil recovery will improve this efficiency in the coming decades.

The actual calculation behind Table 4.24 involve a number of trajectory diagrams and pages of calculations. All of these cannot be reproduced in this handbook, but it may be useful to present a brief example. Table 4.25 shows the summary of data from the CERI petroleum-to-gasoline trajectory, after the trajectory inputs have been disaggregated by fuel type to represent the appropriate geographical mix. In this case, it is assumed that a U.S. average of energy use in the petroleum-to-gasoline trajectory is appropriate.

The CERI trajectories for fossil fuels to electricity were recalculated using the mix of Colorado electrical generation by fuel type.

In using these coefficients, it is not necessary to multiply direct energy by the coefficients to obtain indirect energy, and then add the direct energy to the indirect energy. The direct energy is included in the multiplier; if direct and indirect energies were added, then direct energy would be double-counted.

This method of calculating indirect energy is more precise than using economic input-output data as has been used in some studies. The input-output data was used for materials energy calculations in the CERI study. Inasmuch as this is now one order removed in this handbook due to the process of using trajectory data as the first-order input into the direct energy calculations, inaccuracies in the I-O data become even less significant.

TABLE 4.24

INDIRECT ENERGY COEFFICIENTS

Note on use of this table: The coefficients in this table are to be used to calculate the total external energy required to "drive" the operations of a module. The coefficients represent direct and indirect energy inputs; i.e., they represent the entire trajectory energy as various types of resources in the ground which supports the input of a unit of direct energy of a specific type. Since these coefficients include direct energy and indirect energy, it is not necessary to add the direct energy in with the indirect energy input. These coefficients are used to multiply direct energy (which are entered on a standard module as item (6) by type of direct energy input) by the row of coefficients for that type of direct energy; the product is the total indirect energy by type, (to be entered in item (8) on the standard module worksheet.

For example, if a module worksheet shows direct energy input of 2×10^{12} Btu of gasoline (16×10^6 gallons at 125,000 Btu/gallon), the total energy (direct plus indirect) as resources in the ground is:

$$\frac{2 \times 10^{12}\text{ Btu}}{1 \times 10^{6}\text{ Btu}} = (2 \times 10^{6}\text{ Btu}) \text{ times each coefficient:}$$

Crude Oil	Natural Gas	Coal	Hydro	Nuclear
$(2 \times 10^6)(2.279 \times 10^6)$ $= 4.558 \times 10^{12}$	$(2 \times 10^6)(75.28 \times 10^3)$ $= 150.6 \times 10^9$	$(2 \times 10^6)(14.7 \times 10^3)$ $= 29.4 \times 10^9$	$(2 \times 10^6)(2.6 \times 10^3)$ $= 5.2 \times 10^9$	0

DIRECT ENERGY TYPE *		INDIRECT ENERGY: RESOURCES IN THE GROUND, Btu				
		Crude Oil	Natural Gas	Coal	Hydro	Nuclear
Electricity	1.0×10^6 Btu (for 1 kwh:)	70×10^3 (240)	1.389×10^6 (4740)	1.509×10^6 (5150)	173×10^3 (590)	0 (0)
Gasoline	1.0×10^6 Btu (for 1 gallon:)	2.279×10^6 (284,850)	67.70×10^3 (9,410)	14.7×10^3 (1,840)	2.6×10^3 (330)	0 (0)
Diesel and Fuel Oil	1.0×10^6 Btu (for 1 gallon:)	2.119×10^6 (305,640)	67.70×10^3 (10,470)	14.70×10^3 (2,040)	2.6×10^3 (360)	0 (0)
Natural Gas	1.0×10^6 Btu (for 1 mcf:)	22.00×10^3 (22.00×10^3)	1.103×10^6 (1.103×10^6)	2.1×10^3 (2.1×10^3)	200 (200)	0 (0)

* Colorado region for production of each energy type.

TABLE 4.25

Indirect Energy Determination Example: Petroleum-To-Gasoline

For entire gasoline trajectory; per 8 gallons gasoline (1 x 106 Btu) as final product.

	Resources in the Ground				
Resource Type:	Coal	Natural Gas	Petroleum	Hydro	Nuclear
Energy					
Direct External	0	61,200	3,600	0	0
Indirect External	14,700	14,100	17,100	2,600	0
Internal Consumption and Principal Energy Loss	0	0	8,610	0	0
Sum	14,700	75,300	28,810	2,600	0
Unrecovered Resource of Principal Energy	0	0	2,250,000	0	0
Sum	14,700	75,300	2,278,800	2,600	0
Per 1 gallon gasoline	1,840	9,410	284,850	325	0

4.2.3 Materials Energy

As discussed in Section 2, there are several methods of calculating materials energy. In general, the approach has been to use these approach in the following priority, based on the availability of data:

Priority	Method
1	Obtain tonnage of material; multiply by Btu/ton from engineering analyses of energy required to extract raw materials, process in to basic materials and fabricate into finished products.
2	Use priority 1 method for maximum data; augment or modify with Btu/$ data times $/ton.
3	Use Btu/$ of purchases from Census of Manufactures and U.S. Input-Output tables, as developed by University of Chicago at Urban-Champaign (Herendeen and Ballard).

In the case of the priority 1 approach, extensive calculations were necessary to accomplish the following:

(1) Compare BTU/ton for various materials from several studies done for the Bureau of Mines, Department of Energy, and others.

(2) Where item (1) above terminated in basic materials (steel, iron, aluminum, etc.) rathere than fabricated products and equipment, estimate the additional energy needed for fabrication. This was done using data from Oak Ridge Associated Universities (ORAU) in general. However, that source contains some obvious inaccuracies which were smoothed out and adjusted by comparing with other sources of information, including proprietary CSMRI studies for industry. For example, the following ORAU data were averaged, partially for "smoothing" and partially because the aggregation of equipment available to CSMRI was less detailed than the ORAU breakdown:

Construction Machinery	94×10^6 Btu/ton
Industrial Trucks	92×10^6 Btu/ton
Oilfield Machinery	173×10^6 Btu/ton
Motor Vehicles	137×10^6 Btu/ton
Average	124×10^6 Btu/ton

This figure was used for all construction, mining and railroad equipment in this handbook. Simimlar calculations were made for other groups of products.

(3) The direct energy consumptions as developed in (1) and (2) above were multiplied by indirect energy multipliers, broken down by fuel type, to get total energy resources in the ground.

(4) In some cases, such as the module on natural gas in section 6, tonnages of materials could not be obtained within the scope of this project, and Btu/$ figures were used, from the priority 3 approach mentioned above.

Table 4.26 summarizes the materials energy information used. For each module, the standard form gives the materials, their quantities, the multipliers from Table 4.26, and the energy by type for each quantity of material. As an example, if a process has 2 tons/year of aluminum transmission wire, the oil represented is $2(73.3 \times 10^6) = 146.6 \times 10^6$ Btu.

4.2.4 Infrastructure Energy

Discussion of Process

The basic approach to infrastructure energy was presented in Section 2. It is noted that the energy data are to be assisgned to the total population which is associated with the entire trajectory, or, for a regional analysis, the sum of all trajectories for the regional action.

The methodology for determining energy consumption by energy type per capita is as follows (refer to Figure 2.4 for reference).

First, it is assumed for the purposes of this handbook that the population involved in oil shale development will live in counties such as Mesa and Moffat counties, Colorado, or in other counties with similar energy consumption patterns. These patterns differ somewhat from major urban areas and from non-Western rural areas. Therefore, the best available information for Mesa and Moffat counties was used to obtain residential, commercial and transportation energy consumption for the year 1977. Data were not available for propane, oil, coal, wood, and kerosene for those counties for the residential and commercial sectors, as well as all transportation fuels except gasoline, so state averages were assumed to apply to those counties. Direct use was as follows:

Annual Average Consumption per Capita

Residential:		
Electricity	2.64×10^3 kwh	2.22×10^3 kwh
Natural gas	52.73×10^3 cf	49.54×10^3 cf
Oil	22.3 gal	22.3 gal
Propane	36.33 gal	36.33 gal
Other	1.28×10^6 Btu	1.28×10^6 Btu
Commercial:		
Electricity	3.67×10^3 kwh	2.90×10^3 kwh
Natural gas	27.7×10^3 cf	21.6×10^3 cf
Oil	39.0 gal	39.0 gal
Propane	25.7 gal	25.7 gal
Other	8.00×10^6 Btu	8.00×10^6 Btu
Transportation:		
Gasoline	533 gal	569 gal
Diesel	78 gal	78 gal
Natural gas	3061 cf	3061 cf
Augas, jet fuel	10^6 gal	10^6 gal

Next adjustments were made to reflect probable changes in consumption per capita by 1990. For transportation, it was assumed that per capital consumption would be 75% of the 1977 consumption. Other consumption was

TABLE 4.26

Materials Energy

Material	Units	Btu/Unit, Resources in the Ground Oil	Gas	Coal	Hydro	Nuclear
Aluminum Transmission	ton	73.3x10^{6}	66.8x10^{6}	102.4x10^{6}	16.4x10^{6}	21.1x10^{6}
Asphalt	Bbl	9.116x10^{6}	306.8x10^{3}	59.90x10^{3}	10.60x10^{3}	0
Concrete in place	ton	5.450x10^{6}	1.301x10^{6}	2.659x10^{6}	78.40x10^{3}	576.2x10^{3}
Rock, Limestone	ton	157.5x10^{3}	7.171x10^{3}	19.43x10^{3}	1.382x10^{3}	9.60x10^{3}
Rubber Products	ton	14.94x10^{6}	11.09x10^{6}	15.84x10^{6}	734.9x10^{3}	3.576x10^{3}
Steel structures, track, pipe, reinforcing, siding	ton	12.03x10^{6}	18.45x10^{6}	53.01x10^{6}	363.8x10^{3}	2.787x10^{6}
Materials handling equipment: Steel parts other than structures	ton	19.49x10^{6}	30.08x10^{6}	86.42x10^{6}	601.6x10^{3}	4.613x10^{6}
Mechanical and electrical equip, pipes	ton	23.14x10^{6}	68.83x10^{6}	85.63x10^{6}	2.302x10^{6}	18.15x10^{6}
Steam Generator	ton	55.30x10^{6}	84.85x10^{6}	225.4x10^{6}	76.10x10^{3}	26.59x10^{3}
Mining Machinery	ton	16.11x10^{6}	24.82x10^{6}	71.18x10^{6}	489.2x10^{3}	3.748x10^{6}
Baghouse, scrubber, water treatment equipment	ton	22.13x10^{6}	34.02x10^{6}	97.87x10^{6}	677.1x10^{3}	5.189x10^{6}
Railroad equipment, construction and trucking equipment	ton	21.18x10^{6}	32.71x10^{6}	93.95x10^{6}	651.9x10^{3}	4.997x10^{6}
Turbine, electrical	ton	20.27x10^{6}	60.08x10^{6}	74.81x10^{6}	2.010x10^{6}	15.85x10^{6}
Motors, pumps	ton	23.70x10^{6}	36.64x10^{6}	105.3x10^{6}	727.2x10^{3}	5.577x10^{6}
Timbers	ton	33.5x10^{3}	1.0x10^{3}	0	0	0
Explosives (ANFO)	ton	9.029x10^{6}	20.03x10^{6}	95.3x10^{6}	13.5x10^{3}	0
Copper Wire	ton	76.26x10^{6}	69.31x10^{6}	29.3110^{6}	1.76x10^{6}	13.26x10^{6}

adjusted to reflect a decreasing per capita consumption and a shift to an increased percentage of electricity in the entire mix. The figures were based on a total U.S. consumption of 114 quads in the year 2000, as discussed in "Energy in America's Future" published by Resources for the Future.

The results of all the calculations are presented in Table 4.27. These figures are resources in the ground for all types of consumption (residential, commercial, transportation and industrial) demands on a per capita basis. To use these figures in this handbook, it is simply necessary to identify the population which is associated with all modules which are of a geographic relevance in any trajectory (or sum of trajectories in a regional analysis) and multiply the population by the per capita energy consumption data of Table 4.27.

4.2.5 Conversion Factors

Conversion factors are presented in Table 4.28.

TABLE 4.27

Infrastructure Energy

Per Capita Resources in the Ground

Petroleum	388.9×10^6 Btu
Natural Gas	191.3×10^6 Btu
Coal	196.5×10^6 Btu
Hydropower	124.5×10^6 Btu
Nuclear	28.09×10^6 Btu
Total	929.29×10^6 Btu

Table 4.28

Conversion Factors

(1) Forms of Energy to Btu.(1)

Form	Standard Units	Btu Equivalent
Natural Gas	Scf	1,000(1)
Coal	Ton	20,000,000(2)
Crude Oil	Bbl.	5,800,000
Gasoline	gal.	125,000
Diesel	gal.	139,000
Fuel Oil	gal.	139,000
Residual	gal.	150,000
Electricity	KwH	3,413(4)
Hydropower	KwH	3,413
Petroleum coke	bbl.	6,024,000(5)
Wood	lb.	5,500

(1) A Btu (British thermal unit) is the amount of heat required to raise the temperature of 1 lb. of water 1° Fahrenheit. It equals 3.97 Kcal (Kilocalories) or 3,970 calories. The average person needs 8000 Btu/day for sustenance. This is about 2,000 Kcal, which are used in diet measurements, or 2,000,000 calories.

(2) At sea level, one scf of natural gas normally has an energy value of 1035 Btu. However, at higher elevations, this value decreases, and is below 900 Btu/scf in some utility service areas.

(3) Coal ranges from over 26,000,000 Btu/ton for some bituminous coals down to about 13,000,000 Btu/ton for some Western lignites. The value in the table is a reasonable average for Western bituminous and sub-bituminous coals.

(4) Electricity and Power:

Energy. The basic unit for energy is the kilowatt-hour (kWh), which is the energy used when a device rated at 1000 watts operates for an hour (or a 100 watt appliance operates for 10 hours).

Power. The basic unit of power is the watt. For an electrical appliance the power rating is found by multiplying the voltage by the current (in amperes). Thus, a 125 volt appliance drawing 10 amperes has a power rating of 1250 watts. The kilowatt is 1000 watts and a megawatt is a million watts (106) watts. The horsepower is equivalent to 746 watts. In summary:

number of watts = voltage X current
1 kilowatt = 1000 watts = 103 watts
1 megawatt = 1,000,000 watts = 10^6 watts
1 horsepower = 1 hp = 746 watts

(5) At 5.84 barrels per ton.

Table 4.28

Continued

(2) Oil Shale - Heating Value

Shale Grade, G, Gal/Ton (1), (2)	Gross Heating Value, Btu/Pound	Gross Heating Value, Btu/Ton
10.5	1020	2,040,000
17.8	1640	3,280,000
18.8	1600	3,200,000
19.5	1730	3,460,000
21.4	1940	3,880,000
22.3	1990	3,980,000
26.7	2340	4,680,000
29.8	2780	5,560,000
36.3	3080	6,160,000
36.6	3160	6,320,000
38.0	3360	6,720,000
51.8	4480	8,960,000
57.1	5510	11,020,000
61.8	6010	12,020,000
75.0	7000	14,000,000

(1) As determined by Fischer assay.

(2) The relationship can be expressed as equations determined by linear regression:

Btu/lb. = 95,2586 G - 147.89 r = .996
Btu/ton = 190,517.23 G - 295,781.18 r = .996
G = Shale Grade, gal/ton

(3) Source
Stanfield, K.E., 1951, Properties of Colorado oil shale: USBM Report of Investigations 4825.

(e) Data sources

(1) Melcher, A.G., and others, 1976, Net energy analysis--An energy balance study of fossil fuel resources: Golden, Colorado, The Colorado Energy Research Institute.

(2) Bodine, J. Frank and Vitullo, Marshall, 1980; Industrial energy use data book, Oak Ridge, Tennessee, Oak Ridge Associated University.

(3) Frabetti, Alton J. Jr., et al, 1975; A study to develop energy estimates of merit for selected fuel technologies, East Sundwich, Massachusetts, Development Sciences, Inc.

(4) Wolsky, A.M. and Gaines, L.L., 1981; Energy and materials flows in petroleum refining, ARgonne, Illinois, ARgonne National Laboratories.

(5) The MITRE Corporation, 1970; Environmental data for energy technolgoy policy analysis; McLean, Virginia, The MITRE Corporation.

(6) Hayden, J.E. and Levers, W.H., 1973; How to conserve energy while building, expanding a refinery; The Oil and Gas Journal, May 21, 1973, pages 109-116.

5. EXAMPLE TRAJECTORY AND MODULE ANALYSIS, STEP-BY-STEP

Now that the general concept of trajectory (system) design and module (components of the system) analysis has been presented, and the appropriate modules have been discussed in Chapter 4 with the necessary data, an example trajectory can be presented.

The example will be that of a trajectory for producing upgraded shale oil from a surface mine and a direct heated gas flow retort. It will include the use of coke from the oil upgrading for on-site electricity generation. It includes all data needed to produce the answer to Accounting Method 3, which addresses the issue of the recovery and use of resources in the ground. This illustration will be about as complex as any actual trajectory which may confront the user of this handbook.

It must be emphasized that this example is hypothetical. It is close to what a real trajectory might be, but certain assumptions and artificialities have been introduced so that the example will be easier to follow. The real world has been distorted for didactic purposes here.

Before proceeding through the illustration, it might be advisable to state a few ground rules for this step.

(1) Trajectory computation and module computation must be performed concurrently. Normally, the last major module towards the right-hand end of the trajectory will be the starting module for calculations. This "starting module" will be the one whose size or output determines the scale of the system and therefore determines all the rest of the energy and materials inputs, throughputs and losses. In many trajectories, there will be one or more modules to the right of this "starting module."

To illustrate this, in a coal-electric trajectory, the major "starting module" which determines the magnitude of all other quantities will normally be the electric power plant. It is planned to produce a given output, and the development of coal production is then sized to meet the power plant input requirements. In that trajectory, there will normally be one module to the right: the electricity transmission module. Its output will be dependent upon the output from the power plant module, which is the principal energy input to the transmission module, minus the losses which occur as a result of power transmission.

(2) In the calculations of module Principal Energy inputs and product outputs, the input to one module is the output from the module to the left. Therefore, once the Principal Energy input into the starting module has been calculated, this value is the Product Energy Output for the next module to the left. All values for that module can be calculated once the Product Energy output is known; once the Principal Energy input to this module is found, the next module to the left can be addressed, as its Product Energy output is now known.

5.1 Step 1: Design Trajectory

The first step involves designing the trajectory. The concepts discussed in Section 3 must be used. It is necessary to determine whether to account for direct energy only, or to include indirect energy, infrastructure, etc. The accounting method must be selected; here, method 3 will be used. The length of the system must be considered; does the analyst wish to include the energy in transporting the shale oil to a refinery, or not; does the analyst wish to include mining the shale? Normally, the trajectory should include all components of a system from resources in the ground to the last action of the system which is necessary to make the system operate.

For the purposes of this illustration, it has been determined that the modules of the system are those shown on Figure 5.1.

By an interesting coincidence, the trajectory shown in Step 1, Case E, as Figure 3.1e, constitutes the trajectory, and includes the appropriate inputs, study limits and process boundary for application in this example, with one exception. Figure 3.1e does not include the on-site power plant for electricity generation using low-Btu retort gas. This is shown in Figure 3.1c. Adding this module and energy flow to Figure 3.1e gives the actual trajectory for this example, shown on Figure 5.1.

This latter figure is now drawn as a worksheet, Figure 5.1, with spaces for entry of Btu numbers as they are developed. The actual illustration will be pursued as a sequence of steps.

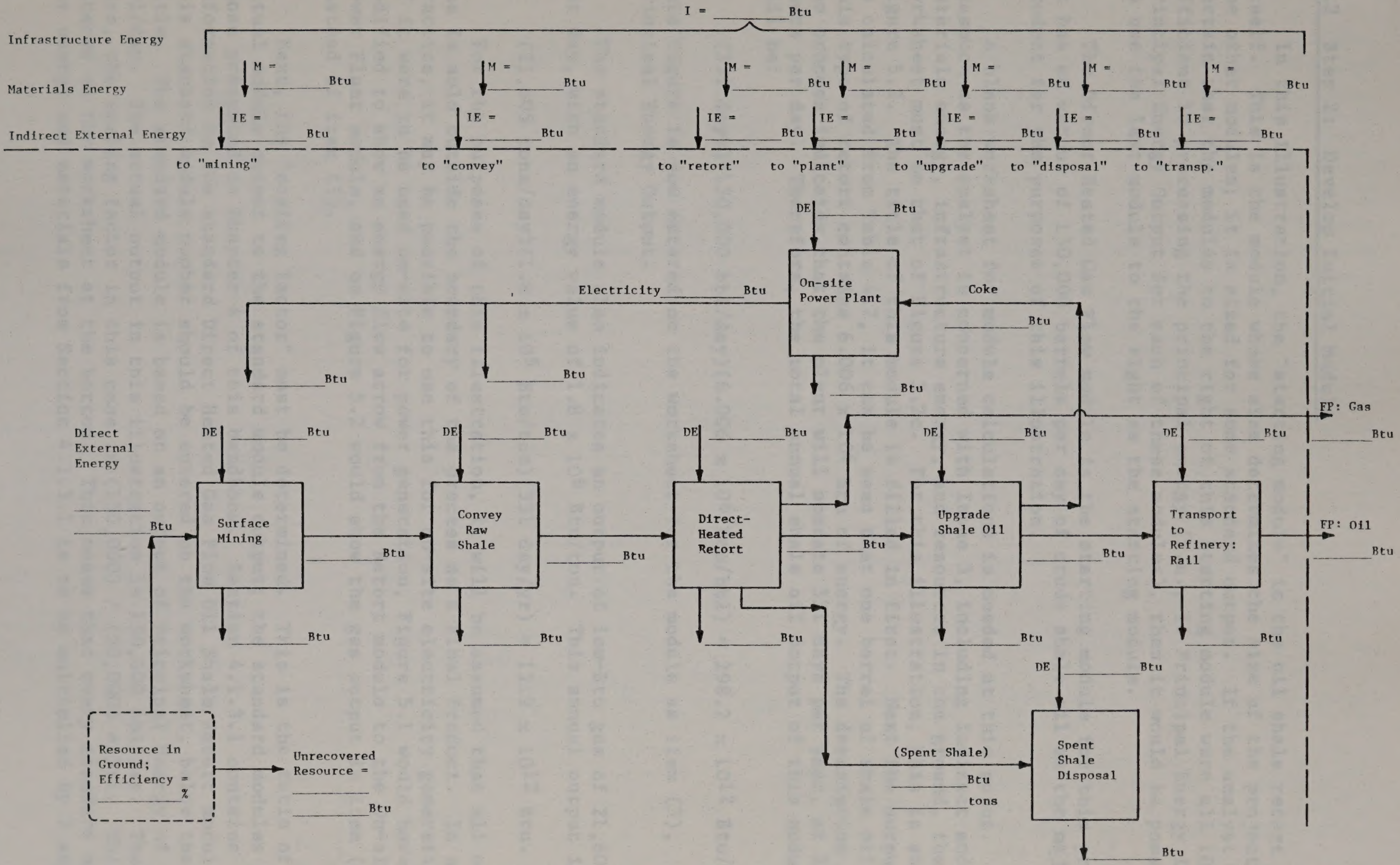


FIGURE 5.1

Illustration Trajectory: Direct Heated Oil Shale Retorting

5.2 Step 2: Develop Initial Module

In this illustration, the "starting module" is the oil shale retort itself. This is the module whose size determines the size of the project and the other modules; it is sized for some standard output. If the analyst were certain that the modules to the right of this starting module were all 100% efficient in processing the principal energy (i.e., if Principal Energy Input = Principal Energy Output for each of these modules), then it would be possible to use the last module to the right as the starting module.

The Direct Heated Gas Flow module is the starting module for this project. It has an output of 150,000 barrels per day of crude shale oil as the major product for the purposes of this illustration.

A blank worksheet for module calculations is needed at this point. Inasmuch as the analyst is concerned with Issue 3, including indirect and materials energy, infrastructure energy, and resources in the ground, the worksheet must be that of Figure 3.2c. For this illustration, this is shown as Figure 5.2. The title of this module is filled in first. Next the output must be calculated from Table 4.7, it can be seen that one barrel of shale oil from this type of retort contains 6.006 x 10^6 Btu of energy. The description of the process indicates that the plant will operate 331 days per year, at 24 hours per day. Therefore, the total annual shale oil output of this module will be:

$$(331 \text{ days})(150{,}000 \text{ bbl/day})(6.006 \times 10^6 \text{ Btu/bbl}) = 298.2 \times 10^{12} \text{ Btu/yr}$$

This figure is now entered on the worksheet for the module as item (3), Principal Energy Output.

The standard module also indicates an output of low-Btu gas of 21,605 tons per day, with an energy value of 1.8 x 10^6 Btu/ton. This annual output is:

$$(21{,}605 \text{ tons/day})(1.8 \times 10^6 \text{ Btu/ton})(331 \text{ day/yr}) = 12.9 \times 10^{12} \text{ Btu.}$$

For the purposes of this illustration, it will be assumed that all of this gas is sold outside the boundary of the process as a Final Product. In actual practice, it may be possible to use this for on-site electricity generation. If it were to be used on-site for power generation, Figure 5.1 would have to be modified to show an energy flow arrow from the Retort module to the On-site Power Plant module, and on Figure 5.2 would show the gas output in item (5) instead of item (3).

Next, the "scaling factor" must be determined. This is the ratio of the actual module output to the standard module output; the standard modules are those presented in Chapter 4 of this handbook. Section 4.1.3.1 contains information on the standard Direct Heated Gas Flow Oil Shale Retort module. This standard module number should be entered on the worksheet, below the title. The standard module is based on an output of Principal Energy of 50,000 bbl/day. The actual output in this illustration is 150,000 bbl/day. Therefore, the scaling factor in this case is (150,000) / (50,000) = 3:1. This is entered on the worksheet at the bottom. This means that every standard number for energy and materials from Section 4.1.3.1 is to be multiplied by 3 and

(10) Grand Total, External Energy Inputs (8)+(9): $\Sigma = 9.148 \times 10^{12}$

Crude Oil	Natural Gas	Coal	Hydropower	Nuclear	Other Energy
357.6×10^{9}	4.026×10^{12}	4.720×10^{12}	10.85×10^{9}	33.23×10^{9}	-

(9) Energy in Materials, by type of energy, as resources in ground.

Material	Quantity, Units	Crude Oil	Natural Gas	Coal	Hydropower	Nuclear	Other Energy
Lumber	48 tons	16.08×10^{6}	48×10^{3}	0	0	0	0
Structural Steel	2,646 "	31.83×10^{9}	48.82×10^{9}	140.25×10^{9}	963×10^{6}	7.37×10^{9}	0
Concrete	7,836 "	42.71×10^{9}	10.19×10^{9}	20.87×10^{9}	614×10^{6}	4.52×10^{9}	0
Equipment Steel	4,626 "	90.15×10^{9}	139.15×10^{9}	399.90×10^{9}	2.78×10^{9}	21.34×10^{9}	0
	Sum, item (9):	164.70×10^{9}	198.15×10^{9}	560.85×10^{9}	3.73×10^{9}	33.23×10^{9}	0

Grand Total, (9): 960.6×10^{9} Btu

(8) Total External Energy as Resources in Ground:

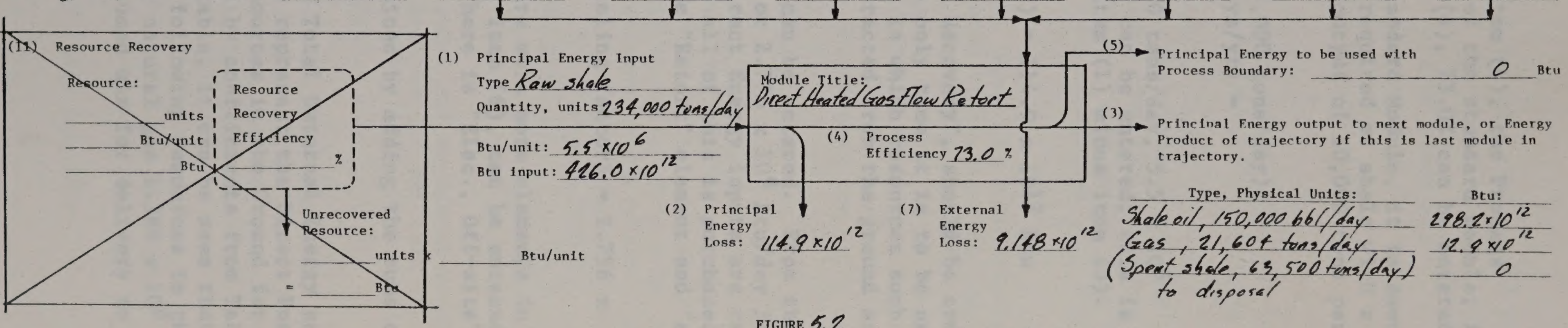
Direct Energy type:	Crude Oil	Natural Gas	Coal	Hydropower	Nuclear	Other Energy
Electric, Off-site	192.92×10^{9}	3.828×10^{12}	4.159×10^{12}	7.12×10^{9}	0	0
Electric, On-site						
Gasoline						
Diesel						
Natural Gas						
Other						
Other						
Sum, item (8):	192.92×10^{9}	3.828×10^{12}	4.159×10^{12}	7.12×10^{9}	0	0

Grand Total, (8): 8.187×10^{12}

(6) Direct External Energy in total Btu's for each element by energy type, and as sum of each energy type for all elements.

Elements:	Elec., Off-site	Elec., On-site	Gasoline	Diesel	Natural Gas	Other	Other
Retort	2.756×10^{12}	0	0	0	0	0	0
Sum, item (6):	2.756×10^{12}	0	0	0	0	0	0

$\Sigma = 2.756 \times 10^{12}$ Btu



(11) Resource Recovery

Resource:

_____ units

_____ Btu/unit

_____ Btu

Resource Recovery Efficiency _____ %

Unrecovered Resource:

_____ units x _____ Btu/unit

= _____ Btu

(1) Principal Energy Input

Type Raw shale

Quantity, units 234,000 tons/day

Btu/unit: 5.5×10^{6}

Btu input: 426.0×10^{12}

Module Title: Direct Heated Gas Flow Retort

(4) Process Efficiency 73.0 %

(2) Principal Energy Loss: 114.9×10^{12}

(7) External Energy Loss: 9.148×10^{12}

(5) Principal Energy to be used with Process Boundary: 0 Btu

(3) Principal Energy output to next module, or Energy Product of trajectory if this is last module in trajectory.

Type, Physical Units:	Btu:
Shale oil, 150,000 bbl/day	298.2×10^{12}
Gas, 21,604 tons/day	12.9×10^{12}
(Spent shale, 63,500 tons/day) to disposal	0

FIGURE 5.2

Module Data for Illustration Trajectory: Direct Heated Oil Shale Retort

Scaling Factor for Standard Module 3.00 Standard Module 4.1.3.1

entered on worksheet 5.2. The one exception is item (4), the Process Efficiency. This stays exactly the same as that of the standard module; in this case it is 73.0%. The information for item (4), 73.0% can be entered.

Item (1) can be addressed next. From the Standard Module, it is seen that this is raw shale feed, with 78,000 tons per day required of shale with a Fischer assay of 30 gallons per ton for a retort output of 50,000 tons per day. For the illustration, item (1) is:

(3.0 scaling factor)(78,000 tons/day) = (234,000 tons/day);
(234,000 tons/day)(5.5×10^6 Btu/ton)(331 days/yr) =
426.0×10^{12} Btu annually

Item (1) can be entered: "Raw Shale, 234,000 tons/day, 5.5×10^6 Btu/ton, 426.0×10^{12} Btu input." Next, item (2) can be entered; this is 3 times the standard module item (2), and is also item (1) minus item (3). Here, it is:

$(426.0 \times 10^{12}) - (298.2 \times 10^{12} + 12.9 \times 10^{12}) = 114.9 \times 10^{12}$ Btu annually.

Item (11), the dashed box labelled "Resource Recovery", should be crossed out or otherwise eliminated from this sheet. The only time it is to be used is for the extreme left-hand module of a trajectory, in which resources such as crude oil, natural gas, coal or oil shale are extracted from the ground and some of the resource is left behind.

Next, the Direct External Energy, item (6), can be entered. From the standard module 4.1.3.1, this is 813,300 kwh/day or 2.776×10^9 Btu/day for a 50,000 tons/day unit, of electricity; no other Direct Energy inputs are required. It is assumed for this illustration that all of this is purchased from off-site. Hence, under item (6), the cell for the "Retort" element and "elec., Off-site" is calculated as:

(2.776×10^9 Btu/day)(331 days/yuear)(3.0 scaling factor) = 2.756×10^{12} Btu annually.

Similar cell calculations would be entered if there were more elements in the module and more types of Direct Energy. The Sum, item (6), can be entered for each energy type. In this case, the only number here is "Elec., Off-site", and is 2.756×10^{12} Btu.

The Grand Total of Direct Energy can be obtained by adding the sums of item (6) and entering at the left of item (6).

Item (8) can be addressed next. This is the Total External Energy as Resources in the Ground. On Figure 5.2, the rows represent the Direct Energy type from item (6); the columns represent the Resources in the Ground for each row. The quantities from item (6) are multiplied by coefficients from Table 4.24, "Indirect Energy Multipliers." From that table, it can be seen that 1×10^6 Btu of electricity can be traced back to the following resources in the ground: coal, 1.509×10^6 Btu; oil 70×10^3 Btu; natural gas 1.389×10^6 Btu, hydropower, 173×10^3 Btu. (This is the assumed mix for delivery to the

oil shale region, based on the Colorado grid.) Hence, the 2.756×10^{12} Btu of off-site electricity equals:

$$\frac{(2.756 \times 10^{12})(70.0 \times 10^{3} \text{ Btu})}{1.0 \times 10^{6}} = 192.92 \times 10^{9} \text{ Btu of crude oil}$$

$$\frac{(2.756 \times 10^{12})(1.509 \times 10^{6} \text{ Btu})}{(1.0 \times 10^{6})} = 4.159 \times 10^{12} \text{ Btu of coal, etc.}$$

These data are entered in item (8); column totals and a Grand Total can be calculated and entered. The Grand Total for item (8) is $8{,}187 \times 10^{12}$ Btu annually.

It is emphasized that all of the data in item (8) represent the sum of direct and indirect external energy. The multipliers from Table 4.24 are set up to include both direct and indirect energy. Hence, it is not necessary to add items (6) to the multiplied numbers of Table 4.24 times item (6); this would double-count the direct energy.

Item (9), Materials Energy, is addressed next. From the standard module 4.1.3.1, it is seen that there are lumber, structural steel, concrete and equipment steel, and the tonnages are given for a 50,000 Bbl/day unit. Looking at concrete, 52,250 tons are required to construct the plant. It is assumed that 3 times this amount is needed for a plant of 150,000 Bbl/day, i.e., the materials quantities are linear with plant size. It is also seen that the plant life is 20 years; hence the annual concrete requirement is:

$$\frac{(52{,}240 \text{ tons})(3.0 \text{ scaling factor})}{20 \text{ years}} = 7{,}836 \text{ tons.}$$

This entered on item (9) in the "Material" and "Quantity, Units" columns. Next, from Table 4.26, "Materials Energy", it can be seen that one ton of concrete in place represents 5.450×10^{6} Btu of oil, 1.301×10^{6} Btu of natural gas, 2.659×10^{6} Btu of coal, etc., as resources in the ground. All that is needed now is to multiply those numbers by the 7,836 tons of concrete and enter the figures in the columns of item (9). For example, the oil resources required for this module's concrete needs are:

$$(5.450 \times 10^{6} \text{ Btu/ton of concrete})(7{,}836 \text{ tons}) = 42.71 \times 10^{9} \text{ Btu}$$

The operation is repeated for lumber, structural steel and equipment steel. The totals for each column, i.e., fuel type, can be found by addition of each column, and a Grand Total can be found by adding the fuel type sums. This Grand Total is 960.6×10^{9} Btu annual for this module.

The Grand Total of all external energy, item (10), can be found by adding items (8) and (9), both by fuel type and by total energy. The item (7), losses of external energy, equals item (10). It is noted that item (6) should not be added into item (10), as (6) is already included in (8) as previously mentioned. Item (10) and (7) are both 9.148×10^{12} annually.

Total losses of Principal Energy and External Energy can be found by adding items (2) and (7); these are:

$$(114.9 \times 10^{12}) + (9.148 \times 10^{12}) = 124.05 \times 10^{12} \text{ Btu annually}$$

This completes the calculations for the module.

5.3 Step 3: Enter Initial Module Data on Trajectory Diagram

The next step is to transfer the summary data or totals from the module worksheet, Figure 5.2, to the trajectory diagram, Figure 5.3. These data include:

Principal Energy Output:	298.2 x 10^{12} Btu
Principal Energy to Final Product as Gas:	12.9 x 10^{12} Btu
Principal Energy Input:	426.0 x 10^{12} Btu
Losses (at bottom of box): (These are the total of items (2) and (7) from Figure 3.4a)	124.05 x 10^{12} Btu
DE = Direct Energy: (This is item (6) from Figure 3.4a)	2.756 x 10^{12} Btu
IE = Indirect Energy: (This is item (8) of Figure 3.4a)	8.187 x 10^{12} Btu
M = Materials Energy: (This is item (9) of Figure 3.4a)	9.60.6 x 10^{9} Btu
Spent Shale (to disposal)	63.1 x 10^{6} tons

Note that "IE" includes "DE" within it, according to the calculation method used in this handbook. If the analyst adds "IE" and "DE", the "DE will be double counted; therefore, such an addition should never be made. This warning will be repeated later.

The spent shale to "Spent Shale Disposal" must also be entered. This is identified for the standard module, 4.1.3.1, and multiplied by the scaling factor which is 3 in this case. Both the tonnage of spent shale and the total Btu's of energy left in the shale should be entered on the figure. No other data or numbers can be entered on Figure 5.3 until calculations are made on another module.

It is possible to move to the next module upstream or left of the starting module, or to the next module downstream or right of the starting module. In this case, the downstream module will be addressed next. The reason for this is that "Upgrade Shale Oil" results in a co-product of coke which is a feasible fuel for on-site electricity generation. For the purposes of this illustration, it will be assumed that this co-product is indeed used within the site boundary for electricity generation.

The implications of this are several.

(1) First, the on-site electricity replaces the purchase of off-site electricity, and thus completely alters the amount and types of "resources-in-the-ground" needed for electricity generation.

(2) Second, the overall external inputs, and hence the entire energy balance and ratios for the trajectory, are altered.

(3) Materials energy and infrastructure energy will be slightly altered.

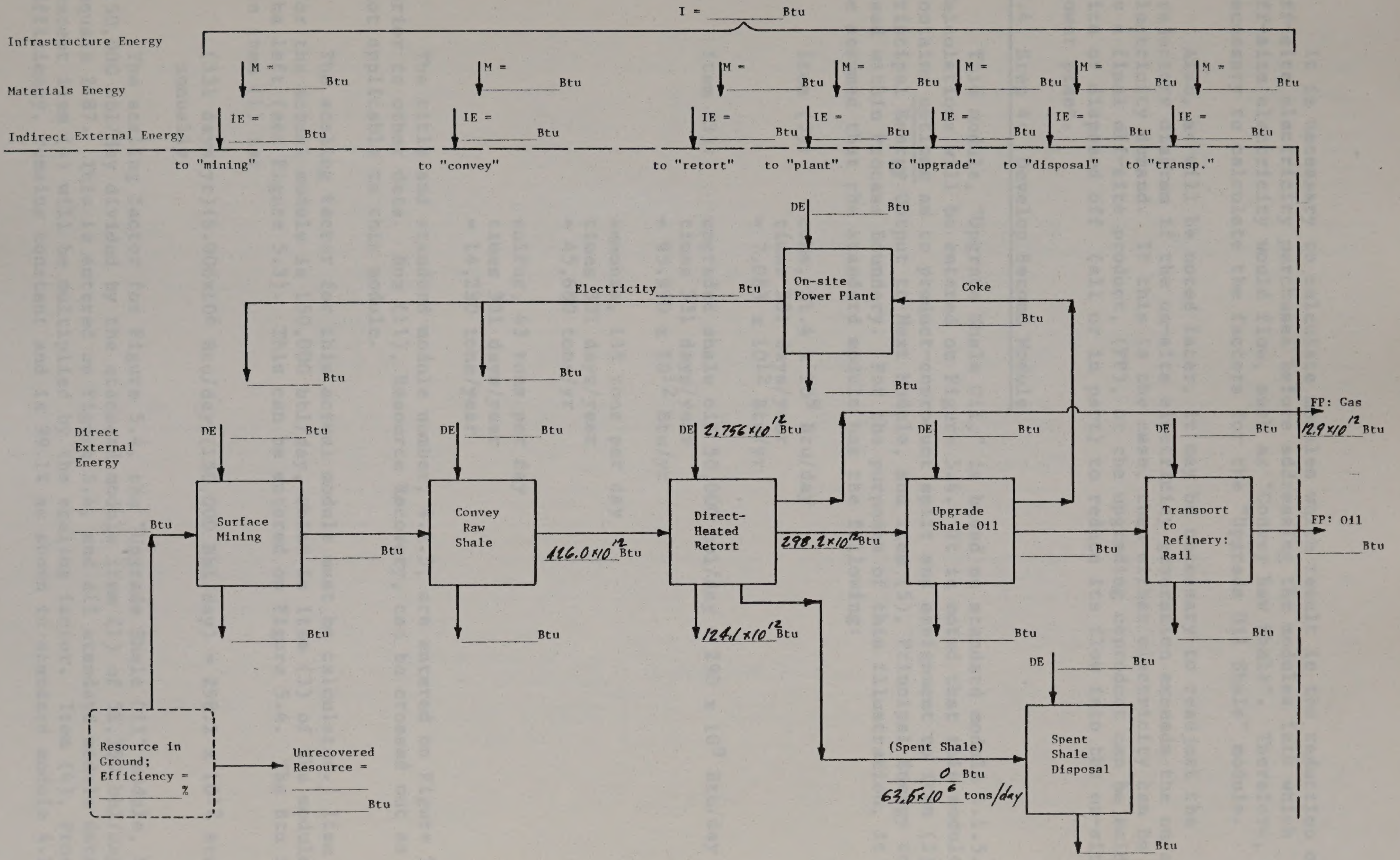


FIGURE 5.3

Illustration Trajectory: Direct Heated Oil Shale Retorting

It is necessary to calculate modules which result in the reduction of off-site electricity purchases before addressing the modules into which off-site electricity would flow, such as "Convey Raw Shale". Therefore, it is necessary to calculate the factors for the "Upgrade Oil Shale" module.

Also, as will be noted later, it may be necessary to readjust the trajectory diagram if the on-site electricity generation exceeds the on-site electricity demand. If this is the case, then either electricity can be sold as a final off-site product, (FP), or the upgrading coproduct can be sold off site or disposed off (all or in part) to reduce its flow into the on-site power plant.

5.4 Step 4: Develop Second Module

This module, "Upgrade Shale Oil," is based on standard module 4.1.5. Calculations will be entered on Figure 5.4. It is noted that this module contains options as to product-coproduct split and assignment to item (3), Principal Energy Output to Next Module, and item (5), Principal Energy to be used within Process Boundary. For the purposes of this illustration, it will be assumed that the standard module has the following:

item (5):	coke, 21.4 x 10^9 Btu/day times 331 days/year = 7.083 x 10^{12} Btu/yr
item (3):	upgraded shale oil 50,000 bbl/day = 290 x 10^9 Btu/day times 331 days/year = 95.990 x 10^{12} Btu/yr
	ammonia, 138 tons per day times 331 days/year = 45,680 tons/yr
	sulfur, 43 tons per day times 331 days/year = 14,230 tons/year

The title and standard module number, 4.1.5, are entered on Figure 5.4 prior to other data. Box (11), Resource Recovery, can be crossed out as it is not applicable to this module.

The scaling factor for this actual module must be calculated. Item (1) for the actual module is 150,000 bbl/day, which is item (3) of the module to the left (see Figure 5.3). This can be entered on Figure 5.4. The Btu input in item (1) is:

(331 days/yr)(6.006x10^6 Btu/day)(150,000 Bbl/day) = 298.2 x 10^{12} Btu annually

The scaling factor for Figure 5.4, the "Upgrade Shale Oil" module, is 150,000 bbl/day divided by the standard module item (1) of 52,350 bbl/day; this equals 2.87. This is entered on Figure 5.4, and all standard module data except item (4) will be multiplied by the scaling factor. Item (4), Process Efficiency, remains constant and is 99.1% as shown in standard module 4.1.5.

(10) Grand Total, External Energy Inputs (8)+(9): $\Sigma = 58.227 \times 10^{12}$ Btu

Crude Oil	Natural Gas	Coal	Hydropower	Nuclear	Other Energy
1.356×10^{12}	55.856×10^{12}	947.8×10^{9}	16.9×10^{9}	50.4×10^{9}	

(9) Energy in Materials, by type of energy, as resources in ground.

Material	Quantity, Units	Crude Oil	Natural Gas	Coal	Hydropower	Nuclear	Other Energy
Lumber	(See module 4.1.5)	24.2×10^{6}	72×10^{3}	0	0	0	
Structural Steel		47.9×10^{9}	73.5×10^{9}	208.2×10^{9}	1.5×10^{9}	11.1×10^{9}	
Concrete		64.3×10^{9}	15.3×10^{9}	31.4×10^{9}	914×10^{6}	6.8×10^{9}	
Equipment Steel		135.7×10^{9}	209.4×10^{9}	602.4×10^{9}	4.5×10^{9}	32.5×10^{9}	
	Sum, item (9):	247.9×10^{9}	298.2×10^{9}	842.0×10^{9}	6.8×10^{9}	50.4×10^{9}	

Grand Total, (9): 1.445×10^{12} Btu

(8) Total External Energy as Resources in Ground:

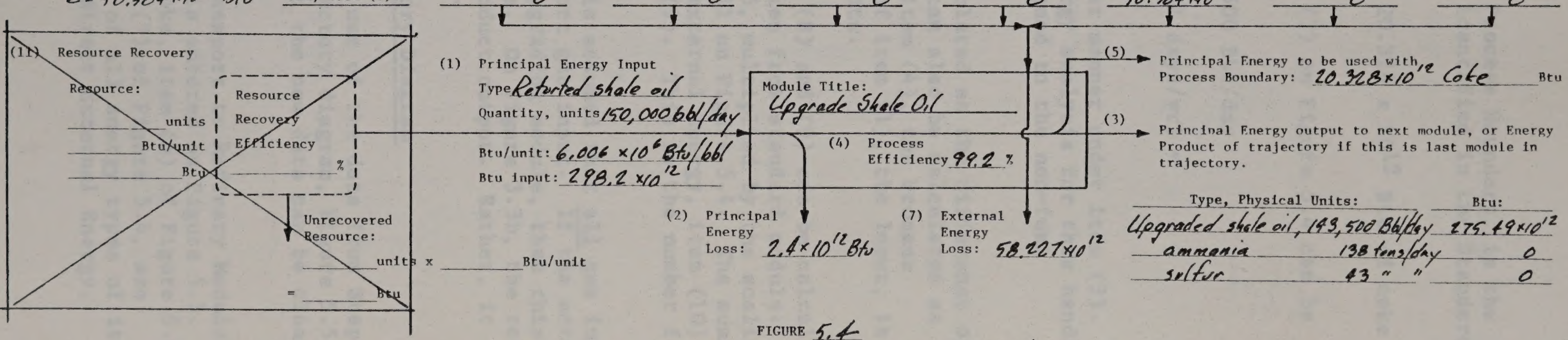
Direct Energy type:	Crude Oil	Natural Gas	Coal	Hydropower	Nuclear	Other Energy
Electric, Off-site						
Electric, On-site						
Gasoline						
Diesel						
Natural Gas	1.108×10^{12}	55.558×10^{12}	105.8×10^{9}	10.1×10^{9}	0	
Other						
Other						
Sum, item (8):	1.108×10^{12}	55.558×10^{12}	105.8×10^{9}	10.1×10^{9}	0	

Grand Total, (8): 56.782×10^{12} Btu

(6) Direct External Energy in total Btu's for each element by energy type, and as sum of each energy type for all elements.

Elements:	Elec., Off-site	Elec., On-site	Gasoline	Diesel	Natural Gas	Other	Other
Upgrading	0	0	0	0	50.384×10^{12}	0	0
Sum, item (6):	0	0	0	0	50.384×10^{12}	0	0

$\Sigma = 50.384 \times 10^{12}$ Btu



~~(11) Resource Recovery~~

~~Resource:~~

~~______ units~~

~~______ Btu/unit~~

~~______ Btu~~

~~Resource Recovery Efficiency ______ %~~

~~Unrecovered Resource: ______ units x ______ Btu/unit = ______ Btu~~

(1) Principal Energy Input

Type Retorted shale oil

Quantity, units 150,000 bbl/day

Btu/unit: 6.006×10^{6} Btu/bbl

Btu input: 298.2×10^{12}

Module Title: Upgrade Shale Oil

(4) Process Efficiency 99.2 %

(2) Principal Energy Loss: 2.4×10^{12} Btu

(7) External Energy Loss: 58.227×10^{12}

(5) Principal Energy to be used with Process Boundary: 20.328×10^{12} Coke Btu

(3) Principal Energy output to next module, or Energy Product of trajectory if this is last module in trajectory.

Type, Physical Units:		Btu:
Upgraded shale oil,	143,500 Bbl/day	275.49×10^{12}
ammonia	138 tons/day	0
sulfur	43 " "	0

FIGURE 5.4

Module Data for Illustration Trajectory: Upgrade Shale Oil Module

Scaling Factor for Standard Module 2.87 Standard Module 4.1.5

Item (5), Principal Energy to be used within Process Boundary, is the scaling factor times the heating value of coke as identified in the Standard Module 4.1.5. This is:

(2.87 scaling factor)(7.083 x 10^{12} Btu/yr) = 20.328 x 10^{12} Btu of coke annually

Similarly, the Principal Energy Output, item (3) on Figure 5.4 can be calculated; it is upgraded shale oil:

(2.87 scaling factor)(50,000 Bbl/day) = 143,500 Bbl/day

and

(2.87 scaling factor)(290.0 x 10^9 Btu/day)(331 days/yr) = 275.49 x 10^{12} Btu annually

Ammonia and sulfur can also be entered in a similar manner under item (3). However, according to the ground rules of net energy analysis for this handbook as stated in Section 2.6, no energy value is assigned to the non-fuel by-products.

Item (2), Principal Energy Loss, can be calculated as the difference of item (1) minus the sum of items (3) and (5). It can also be calculated as (100% - item (4)) times item (1). In this case, item (4), the Process Efficiency is 99.1%, so (100.00% - 99.1%) = 0.9% of item (1), the Input, is lost as item (2). The figure here is 2.4 x 10^{12} Btu.

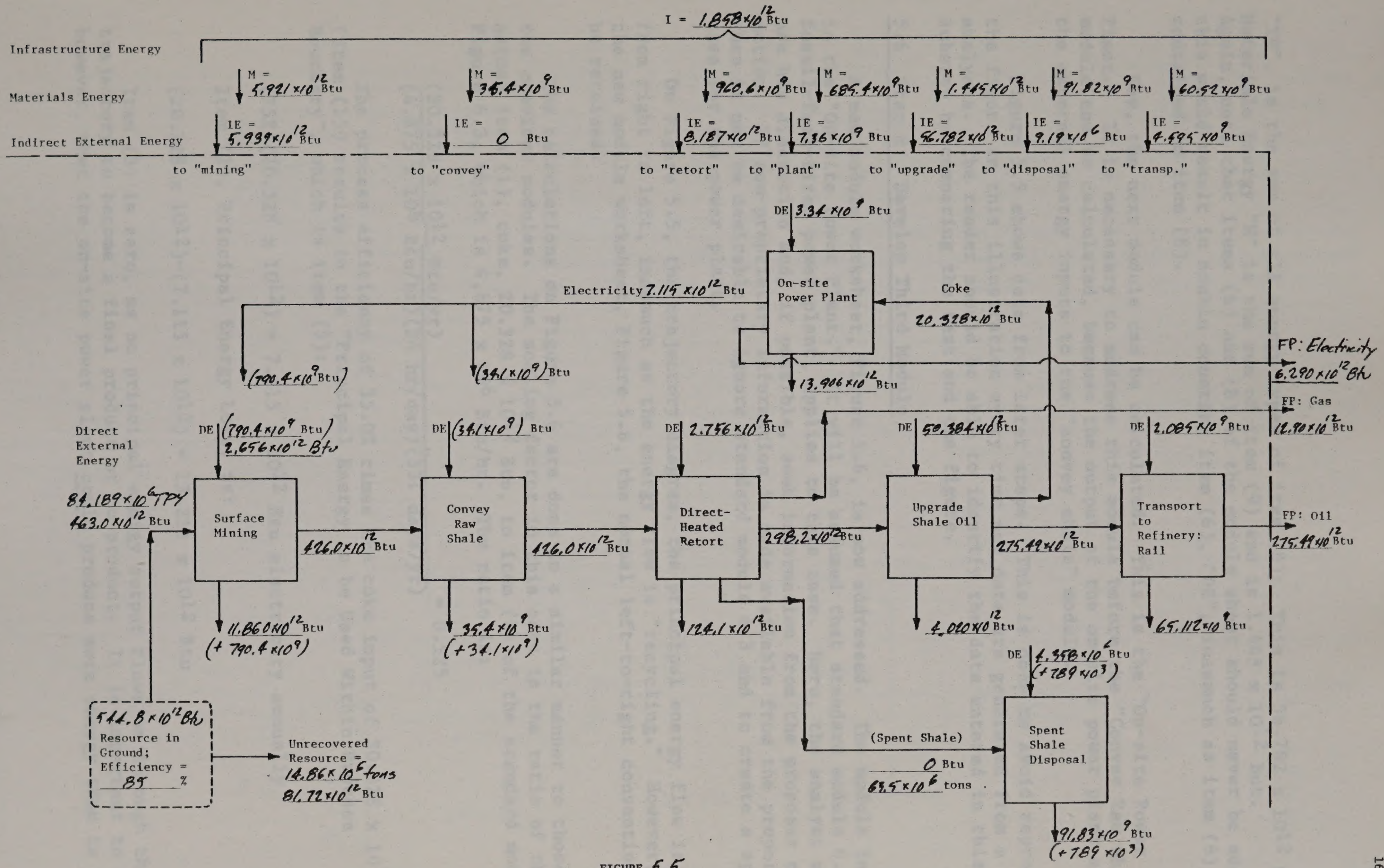
The balance of the information of items (6), (8) and (9) can be calculated as in the first module. The standard data are taken from standard module. The standard data are taken from standard module 4.1.5, multiplied by the scaling factor of 2.87, and entered in the appropriate cell on Figure 5.4. The sums of item (6), (8) and (9) can be entered. The total external energy, item (10), can be found by adding the sums of items (8) and (9). This is the number for entry into item (7); it is 58.227 x 10^{12} Btu.

For simplification in this illustration, it is assumed that all gas input in item (6) is purchased natural gas, with no retort gas input. If the actual trajectory uses retort gas as an input into the upgrading module, then this would be indicated on Figures 3.3b and Figure 3.4a. On Figure 3.3b, the retort gas output arrow would not be drawn as a Final Product output. Rather, it would go into the upgrade module, to replace "DE".

5.5 Step 5: Enter Second Module Data on Trajectory Diagram

This step is a duplicate of Step 3, with the use of the data from Step 4.4 and Figure 5.4. In this illustration, a new trajectory diagram, Figure 5.5, will replace Figure 5.3 used in Substep 3, so that the new data can be clearly identified.

"Upgrade Shale Oil Module" output to the "Transport to Refinery Module" is 275.491 x 10^{12} Btu, item (3) of Figure 5.4; this is entered on Figure 5.5. The energy flow to the "On-site Power Plant" is coke, item (5) of Figure 5.4, and is 20.328 x 10^{12} Btu. The total losses, item (7) of Figure 5.4, are 58.227 x 10^{12} Btu. Direct Energy "DE" is the sum of all energy types of item (6) on Figure 5.4; this is 50.384 x 10^{12} Btu. Indirect External Energy,



I = 1.858×10^{12} Btu
Infrastructure Energy
Materials Energy
Indirect External Energy
M = 5.921×10^{12} Btu
M = 35.4×10^{9} Btu
M = 960.6×10^{9} Btu
M = 685.4×10^{9} Btu
M = 1.445×10^{12} Btu
M = 91.82×10^{9} Btu
M = 60.52×10^{9} Btu
IE = 5.939×10^{12} Btu
IE = 0 Btu
IE = 8.187×10^{12} Btu
IE = 7.36×10^{9} Btu
IE = 56.782×10^{12} Btu
IE = 9.19×10^{6} Btu
IE = 4.595×10^{9} Btu
to "mining"
to "convey"
to "retort"
to "plant"
to "upgrade"
to "disposal"
to "transp."
DE 3.34×10^{9} Btu
On-site Power Plant
Electricity 7.115×10^{12} Btu
Coke
20.328×10^{12} Btu
13.906×10^{12} Btu
$(790.4 \times 10^{9}$ Btu)
(34.1×10^{9}) Btu
FP: Electricity
6.290×10^{12} Btu
FP: Gas
12.90×10^{12} Btu
Direct External Energy
DE $(790.4 \times 10^{9}$ Btu)
$2,656 \times 10^{12}$ Btu
DE (34.1×10^{9}) Btu
DE 2.756×10^{12} Btu
DE 50.384×10^{12} Btu
DE 2.085×10^{9} Btu
84.189×10^{6} TPY
463.0×10^{12} Btu
Surface Mining
426.0×10^{12} Btu
Convey Raw Shale
426.0×10^{12} Btu
Direct-Heated Retort
298.2×10^{12} Btu
Upgrade Shale Oil
275.49×10^{12} Btu
Transport to Refinery: Rail
FP: Oil
275.49×10^{12} Btu
11.860×10^{12} Btu
$(+ 790.4 \times 10^{9})$
35.4×10^{9} Btu
$(+34.1 \times 10^{9})$
124.1×10^{12} Btu
4.020×10^{12} Btu
65.112×10^{9} Btu
DE 4.358×10^{6} Btu
$(+789 \times 10^{3})$
544.8×10^{12} Btu
Resource in Ground; Efficiency = 85 %
Unrecovered Resource = 14.86×10^{6} tons
81.72×10^{12} Btu
(Spent Shale)
0 Btu
63.5×10^{6} tons
Spent Shale Disposal
91.83×10^{9} Btu
$(+789 \times 10^{3})$

FIGURE 5.5

Illustration Trajectory: Direct Heated Oil Shale Retorting

"IE", is the sum of all energy types of item (8); This is 56.782 x 10^{12} Btu. Materials Energy "M" is the sum of item (9) and is 1.445 x 10^{12} But. Again, note that items (6) and (8) of the module sheet should never be added; this would result in double counting item (6), "DE", inasmuch as item (6) is contained in item (8).

Now, the next module can be calculated. This is the "On-site Power Plant." It is necessary to address this module before the "Convey Raw Shale" module can be calculated, because the output of the on-site power plant affects the external energy inputs to the "convey shale" module.

Figure 5.5 shows data from later steps. This is done to avoid reproducing the figure in this illustration every time new data are generated from a module analysis. The reader should be able to identify the data entered in this substep by comparing the text and the figure.

5.6 Step 6: Develop Third Module

A new module worksheet, Figure 5.6, is now addressed. The module involved is the "On-site Power Plant." It will be assumed that standard module 6.3, a fossil-fuel-fired power plant, applies to this case. Here, the analyst must use his discretion and, if possible, seek information from the proposer of the action. If non-proprietary information is made available from the proposer, then it may be desirable to ignore standard module 6.3 and to create a special case for the power plant.

On Figure 5.5, the trajectory diagram, the principal energy flow is drawn from right to left, inasmuch as the energy flow is "recycling." However, on the new module worksheet, Figure 5.6, the normal left-to-right convention will be retained.

The calculations on Figure 5.6 are done in a similar manner to those of the previous modules. The scaling factor in this case is the ratio of the actual item (1), coke, 20.328 x 10^{12} Btu, to item (1) of the standard module, Figure 6.3, which is 4,875 x 10^{6} Btu/hr. The ratio is:

$$\frac{(20.328 \times 10^{12}\ \text{Btu/yr})}{(4.875 \times 10^{6}\ \text{Btu/hr})(24\ \text{hr/day})(331\ \text{days/yr})} = 0.525$$

The process efficiency of 35.0% times the coke input of 20.328 x 10^{12} (item (1)) results in the "Principal Energy to be Used Within Process Boundary", which is item (5):

$$(75\%)(20.328 \times 10^{12}) = 7.115 \times 10^{12}\ \text{Btu electricity annually}$$

Item (2), Principal Energy Loss, is:

$$(20.328 \times 10^{12})-(7.115 \times 10^{12}) = 13.213 \times 10^{12}\ \text{Btu}$$

Item (3) is zero, as no principal energy output flows on through the trajectory to become a final product or co-product. It is important to note, however, that the on-site power plant could produce more energy than is needed

(10) Grand Total, External Energy Inputs (8)+(9): Σ=692.76×10^9 Btu	Crude Oil	Natural Gas	Coal	Hydropower	Nuclear	Other Energy
	224.18×10^9	142.32×10^9	299.74×10^9	1.71×10^9	24.8×10^9	

(9) Energy in Materials, by type of energy, as resources in ground.

Material	Quantity, Units	Crude Oil	Natural Gas	Coal	Hydropower	Nuclear	Other Energy
Steel-various	3,176 Tons	62.8×10^9	128.3×10^9	278.4×10^9	941×10^6	20.3×10^9	
Rubber	290 "	314 ×10^6	233 ×10^6	333 ×10^6	15 ×10^6	75 ×10^3	
Limestone	19,000 "	3.0×10^9	136. ×10^6	369 ×10^6	26 ×10^6	182 ×10^6	
Asphalt	12,095 "	110.3×10^9	3.7 ×10^9	724 × 10^6	128 ×10^6	0	
Concrete	7,475 "	40.7×10^9	9.7×10^9	19.9×10^9	586 ×10^6	4.3×10^9	
	Sum, item (9):	217.1×10^9	142.1×10^9	299.7×10^9	1.70×10^9	24.8×10^9	

Grand Total, (9): 685.4×10^9 Btu

(8) Total External Energy as Resources in Ground:

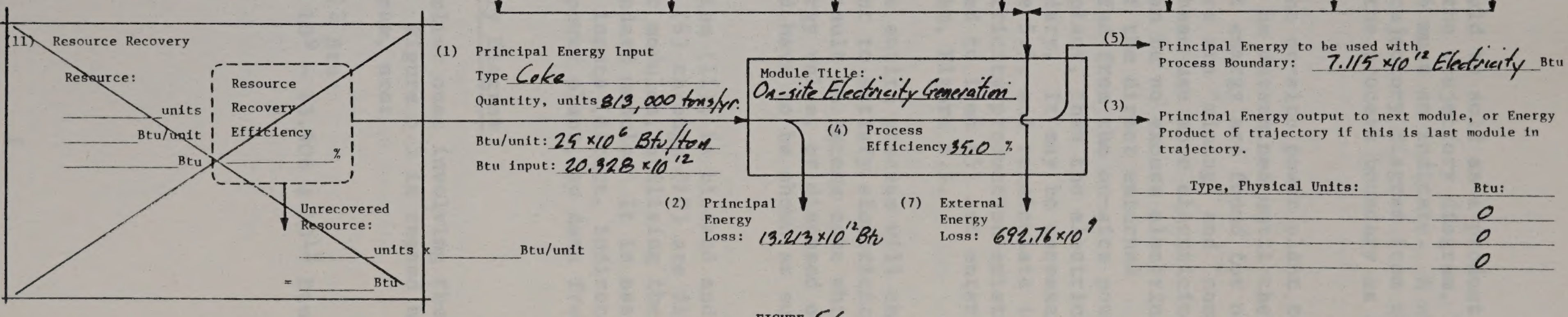
Direct Energy type:	Crude Oil	Natural Gas	Coal	Hydropower	Nuclear	Other Energy
Electric, Off-site						
Electric, On-site						
Gasoline						
Diesel						
Natural Gas						
Other Fuel Oil	7.077×10^9	226×10^6	49.1×10^6	8.7×10^6	–	–
Other						
Sum, item (8):	7.077×10^9	226×10^6	49.1×10^6	8.7×10^6	–	–

Grand Total, (8): 7.361×10^9 Btu

(6) Direct External Energy in total Btu's for each element by energy type, and as sum of each energy type for all elements.

Elements:	Elec., Off-site	Elec., On-site	Gasoline	Diesel	Natural Gas	Other	Other
Power plant	0	0	0	0	0	Fuel Oil 3.34×10^9	0
Sum, item (6):	0	0	0	0	0	3.34×10^9	0

Σ = 3.34×10^9



~~(11) Resource Recovery~~

~~Resource:~~

~~_____ units~~

~~_____ Btu/unit~~

~~_____ Btu~~

~~Resource Recovery Efficiency _____ %~~

~~Unrecovered Resource:~~

~~_____ units x _____ Btu/unit~~

~~= _____ Btu~~

(1) Principal Energy Input

Type Coke

Quantity, units 813,000 tons/yr.

Btu/unit: 25×10^6 Btu/ton

Btu input: 20.328×10^12

Module Title: On-site Electricity Generation

(4) Process Efficiency 35.0 %

(2) Principal Energy Loss: 13.213×10^12 Btu

(7) External Energy Loss: 692.76×10^9

(5) Principal Energy to be used with Process Boundary: 7.115×10^12 Electricity Btu

(3) Principal Energy output to next module, or Energy Product of trajectory if this is last module in trajectory.

Type, Physical Units:	Btu:
	0
	0
	0

FIGURE 5.6

Module Data for Illustration Trajectory: On-site Power Plant Module

Scaling Factor for Standard Module 0.525 Standard Module 6.3

within the process boundary. The excess power could be sold as a product outside the boundary. If this is the case, then the trajectory diagram, Figure 5.5, and the on-site power plant module Figure 5.6 must so indicate. A new energy flow arrow would have to be drawn on the trajectory diagram from the on-site power plant module to the right, exiting the process boundary as the electricity product.

Another caveat here is that the ability of the on-site power plant to provide excess electricity as a trajectory cannot be determined until the external electricity inputs requirements of direct energy are found for other modules which use electricity. In this case, there are "mining" and "convey raw shale." If it is found that one or both of these use more electricity than the on-site power plant can produce, then there can be no excess electricity available as a trajectory co-product. However, if the direct external electricity requirements for the various modules fed from the on-site power plant are less than the production of that power plant, then the electricity co-product is available for sale outside the boundary. It may be necessary to return to the "On-site Power Plant" module, Figure 5.5, and recalculate items (3) and (5) if it is found that an excess of electricity production exists. Some of the energy of item (3) can then be assigned to item (5) and entered on the new energy flow arrow of the trajectory diagram, Figure 5.5.

It is also possible that the management of the entire process will choose to burn only enough coke in the on-site power plant to satisfy electricity demands within the process boundary; this would result in excess coke which could either be sold as a by-product, with an energy value, or disposed of, in which case the coke would be lost energy and would have to be shown as such on the module diagram and trajectory diagram.

On Figure 5.6, the Resource Recovery box, item (11), is blocked and because it is not relevant to this module. Items (6) through (10) are filled in by using the same method as used on the earlier modules, utilizing the scaling factor of 0.525 and the data from the standard module. It is assumed here that the on-site power plant external energy inputs (direct, indirect and materials) are the same as those for an off-site power plant, so data from standard module 6.3 are suitable here.

5.7 Step 7: Enter Third Module Data on Trajectory Diagram

This is another step exactly like the two earlier ones involving the transcription of module data onto the trajectory. Figure 5.5 is reused here. The data entered from Figure 5.6, the module diagram, are:

Plant output : electricity: 7.115×10^{12} Btu
Plant Loss : $13.213 \times 10^{12} + 692.8 \times 10^{9} = 13.906 \times 10^{12}$ Btu
DE : 3.54×10^{9} Btu
IE : 7.36×10^{9} Btu
M : 685.4×10^{9} Btu

5.8 Step 8: Develop Fourth Module

The first module upstream of the starting module is the module titled "Convey Raw Shale." A new worksheet, Figure 5.7, is selected, and the titles are filled in. Item (11), resourse recovery, is blocked out again as it does not enter into the operations of this module. Item (3), Principal Energy Output, for this module can be entered because it is the item (1), Principal Energy Input, of the starting module on Figure 5.2. It has also just been entered on Figure 5.5 between the starting module and the "Convey Raw Shale" module, and is 426 x 10^{12} Btu.

The standard module for "Convey Raw Shale" is number 4.1.2.1, assuming that a conveyor is used. This is entered at the bottom of the figure. The scaling factor must now be determined. This is the ratio of the actual item (3), Principal Energy Output, to item (3) of the standard module. The ratio is:

$$\frac{(77.454 \times 10^6 \text{ Tons})}{(1000 \text{ tons})} = 77.454 \times 10^3$$

The process efficiency from the standard module is 100%, which can be entered as item (4) on Figure 5.7. Item (2), "Principal Energy Loss," is zero inasmuch as 100% of the principal energy input, item (1), flows from left to right through the module. Obviously, item (1) equals item (3); this number can be entered on the figure as 426 x 10^{12} Btu. The other appropriate information on item (1) can also be entered. None of the principal energy is utilized within the process boundary, so zero can be entered as item (5).

The next consideration for the analyst is to determine if all the direct external electricity can be furnished from the on-site power plant, or if some has to be purchased from the outside. The standard module indicates a total direct electricity requirement of 440 x 10^3 Btu to convey 1000 tons of raw shale. Assuming the same conveyor distance and operational characteristics of the standard module, the actual module will require 34.1 x 10^9 Btu of electricity to convey 77.454 x 10^6 tons. This is the scaling factor of 77.454 x 10^3 times the standard 440 x 10^3 Btu of electricity. The on-site power plant provides 7.115 x 10^{12} Btu.

Now, using the scaling factor of 77.454 x 10^3 as just calculated, all of the information of items (6), (8) and (9) can be calculated. This is done by multiplying the appropriate number from the standard module, section 4.1.2.1, by the scaling factor. At this point, the difference between on-site and off-site electricity becomes important. The 34.1 x 10^9 Btu of electricity in item (6) is on-site, and off-site electricity is zero. The on-site electricity does not require any entry in item (8), total external energy as resources in the ground. The reason is that it comes from the resources within this trajectory, and so the indirect energies are internalized within the trajectory. Hence, all of item (8) is zero.

(10) Grand Total, External Energy Inputs (8)+(9): $\Sigma = 35.4 \times 10^9$ Btu

Crude Oil	Natural Gas	Coal	Hydropower	Nuclear	Other Energy
6.61×10^9	7.93×10^9	19.74×10^9	256×10^6	894×10^6	

(9) Energy in Materials, by type of energy, as resources in ground.

Material	Quantity, Units	Crude Oil	Natural Gas	Coal	Hydropower	Nuclear	Other Energy
Steel	194 tons	3.77×10^9	5.82×10^9	16.74×10^9	$116. \times 10^6$	893×10^6	
Rubber	190 "	2.84×10^9	2.10×10^9	3.01×10^9	140×10^6	628×10^3	
	Sum, item (9):	6.61×10^9	7.93×10^9	19.74×10^9	256×10^6	894×10^6	

Grand Total, (9): 35.4×10^9 Btu

(8) Total External Energy as Resources in Ground:

Direct Energy type:	Crude Oil	Natural Gas	Coal	Hydropower	Nuclear	Other Energy
Electric, Off-site						
Electric, On-site						
Gasoline						
Diesel						
Natural Gas						
Other						
Other						
Sum, item (8):	0	0	0	0	0	0

Grand Total, (8): 0

(6) Direct External Energy in total Btu's for each element by energy type, and as sum of each energy type for all elements.

Elements:	Elec., Off-site	Elec., On-site	Gasoline	Diesel	Natural Gas	Other	Other
Conveyor	0	34.1×10^9	0	0	0	0	0
Sum, item (6):	0	34.1×10^9	0	0	0	0	0

$\Sigma = 34.1 \times 10^9$ Btu

(11) Resource Recovery

Resource:

_____ units

_____ Btu/unit

_____ Btu

Resource Recovery Efficiency _____ %

Unrecovered Resource:

_____ units x _____ Btu/unit

= _____ Btu

(1) Principal Energy Input

Type Raw shale, 30 gal/ton

Quantity, units 77.454×10^6 tons

Btu/unit: 5.5×10^6 Btu/ton

Btu input: 426×10^{12}

Module Title: Raw shale conveyor

(4) Process Efficiency 100.0 %

(2) Principal Energy Loss: 0

(7) External Energy Loss: 35.4×10^9 Btu

(5) Principal Energy to be used with Process Boundary: 0 Btu

(3) Principal Energy output to next module, or Energy Product of trajectory if this is last module in trajectory.

Type, Physical Units:	Btu:
Raw shale, 234,000 tons/day	426.0×10^{12}

FIGURE 5.7

Module Data for Illustration Trajectory: Convey Raw Shale Module

Scaling Factor for Standard Module 77.454×10^3 Standard Module 4.1.2.1

Further comment is necessary regarding the fact that the on-site power plant provides 7.115 x 10^{12} Btu, several orders of magnitude more than the amount needed for conveying shale. This indicates that electricity will be available from on-site for mining. If there is an excess available after that, it would be used to replace off-site electricity purchased for the retort as shown in the Retort module worksheet, Figure 3.4a. It would then be necessary to recalculate the Direct Energy, item (6), on that figure, eliminating "off-site" electricity and replacing it by on-site electricity. The Indirect Energy, item (8), data would then change significantly, as would items (10) and (7). Other uses of electricity from the on-site power plant would be in spent shale disposal and water pumpting. If there is still an excess of energy from the on-site plant after all of these uses, then one of two things could be done.

(1) Less coke could be used, thereby reducing the amount of on-site electricity generated some coke could be sold outside the boundary as a Final Product, necessitating a new arrow on the diagram, or it could be disposed of, so that it would become a loss of energy on the "Upgrade Shale Oil" module, Figure 3.4b. This would change the efficiency item (4) on that module.

(2) it could be determined that electricity would be sold as a Final Product. This would necessitate a new arrow from the on-site power plant to the right, crossing the process boundary and becoming an "FP".

At this point, since recalculation of the "Retort" module may be in order, or other assumptions may have to be checked which affect the calculations of items (8), (9), (10) and (7) on the worksheets, it may be desirable to delay calculating those items on the worksheets until the balance and disposition of on-site and off-site electricity in the entire trajectory is determined.

Otherwise, items (8), (9), (10) and (7) can be calculated for Figure 5.7 as just mentioned. To illustrate the materials calculation, the standard module indicates that 5.0 pounds of steel and 4.9 pounds of rubber are neededper 1000 tons. For the annual transportation of 77.454 x 10^6 tons, the annual steel requirements are:

$$\frac{(5.0 \text{ lb})(77.454 \times 10^3)}{(2000 \text{ lb/ton})} = 194 \text{ tons}$$

This steel would be "materials handling steel" for the application of data from Section 4.2.2.

5.9 Step 9: Enter Module Date on Trajectory

Once again, Figure 5.5 is addressed and the data from Figure 5.7 is transferred to it. To remind the analyst that the DE input to the "Convey Raw Shale" module and the use of electricity from the "On-site Power Plant" are internal to the trajectory, they are shown in parentheses as (34.1 x 10^9 Btu). This is also so indicated on the losses from the module.

5.10 Step 10: Calculate Surface Mining Module

A new worksheet, Figure 5.8 is constructed in the same manner as other modules.

The output of the module is 77.454 x 10^6 tons per year. Due to the loss of fines in primary crushing with such fines being unusable in the retort, the input into the module must be 84.189 x 10^6 per year.

One important difference from other modules is that item (11), Resource Recovery, is now relevant and must be addressed. The standard module is section 4.1.1.1. The resource recovery efficiency is 85%, this is entered in item (11). The box in item (11) is drawn as a dashed box to indicate that it is not an operating module, as is shale mining. Rather, it is an accounting device. It is separated from the main module and item (4) so that the analyst can ignore item (11) if his accounting system does not address the issue of resources in the ground. Item (4) is construed to the 100 percent efficiency in this module, because 100 percent of the recovered reserve is mined and none of the mined shale is lost.

The standard module assumes 355 days per year of operation, and the retort is assumed as operating for 331 days per year. The difference is not critical, because the data for the mining standard module are based on 1000 tons of output. One could assume that mining will occur for 331 days per year without significantly affecting the unit data of the standard module.

The total reserve needed to produce 84.189 x 10^6 TYP of raw shale is:

$$\frac{84.189 \text{ x } 10^6 \text{ TYP}}{(0.85 \text{ efficiency})} = 99.05 \text{ x } 10^6 \text{ TPY}$$

The unrecovered reserve is:

$$(99.05 \text{ x } 10^6 \text{ TPY}) - (84.189 \text{ x } 10^6 \text{ TYP}) = 14.86 \text{ x } 10^6 \text{ TPY}$$

The Btu totals are readily calculated, and all the data are entered on the worksheet.

As with Figure 5.7, "Convey Raw Shale", it is assumed that all the electricity for mining will come from the on-site power plant unless it does not have adequate capacity, in which case it would be necessary to supplement it with purchased off-site electricty.

The scaling factor is the energy output, item (3), divided by the standard module output, which is 1000 tons. Hence, the scaling factor is 77.454 x 10^3. For 30 gallon-per-ton shale, the analyst can interpolate on Figure 4.1.1.1 betwen the data for 26 and 34 gallon-per-ton shales. Hence, electricity requirements for crusing per 1000 tons are found:

26 gpt = 831 kwh/1000 tons
30 gpt = x kwh/1000 tons
34 gpt = 727 kwh/1000 tons

	Crude Oil	Natural Gas	Coal	Hydropower	Nuclear	Other Energy
(10) Grand Total, External Energy Inputs (8)+(9): $\Sigma = 11.860 \times 10^{12}$ Btu	6.216×10^{12}	1.177×10^{12}	4.429×10^{12}	12.42×10^{9}	24.70×10^{9}	

(9) Energy in Materials, by type of energy, as resources in ground.

Grand Total, (9): 5.921×10^{12} Btu

	Material	Quantity, Units	Crude Oil	Natural Gas	Coal	Hydropower	Nuclear	Other Energy
crush	Steel-Mat'l Hndl.	1,549 tons	30.19×10^{9}	46.59×10^{9}	133.86×10^{9}	971.9×10^{6}	7.146×10^{9}	
	Concrete	3,292 "	17.94×10^{9}	4.28×10^{9}	8.75×10^{9}	258×10^{6}	1.90×10^{9}	
mine	Steel-Mat'l Hndl.	3,365 "	65.58×10^{9}	101.22×10^{9}	280.8×10^{9}	2.02×10^{9}	15.52×10^{9}	
	Rubber	1,460 "	21.82×10^{9}	16.20×10^{9}	23.17×10^{9}	1.07×10^{9}	5.22×10^{6}	
	Copper	10 "	727×10^{6}	693×10^{6}	294×10^{6}	18×10^{6}	130×10^{6}	
	Explosives	41,244 "	372.39×10^{9}	826.12×10^{9}	3.93×10^{12}	557×10^{6}	0	
		Sum, item (9):	508.68×10^{9}	995.09×10^{9}	4.387×10^{12}	5.418×10^{9}	24.70×10^{9}	

(8) Total External Energy as Resources in Ground:

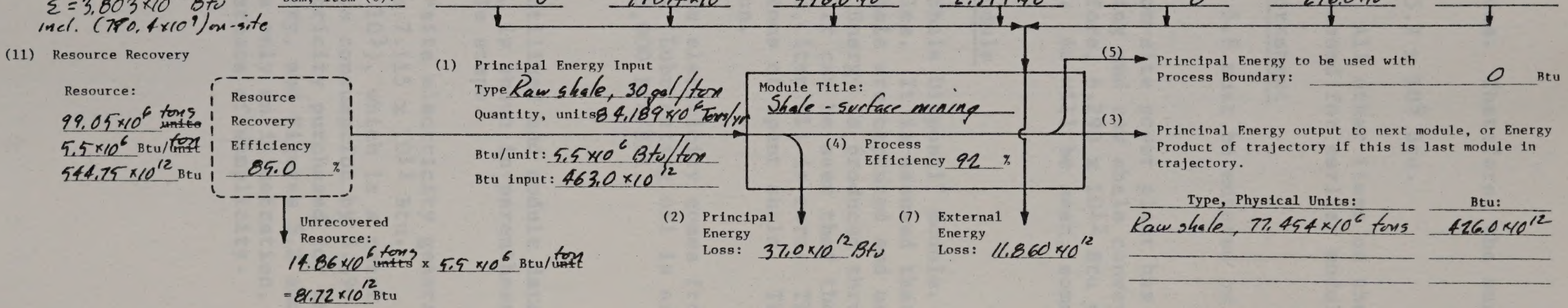
Grand Total, (8): 5.939×10^{12} Btu

Direct Energy type:	Crude Oil	Natural Gas	Coal	Hydropower	Nuclear	Other Energy
Electric, Off-site	0	0	0	0	0	
Electric, On-site	0	0	0	0	0	
Gasoline	81.59×10^{9}	2.434×10^{9}	526×10^{6}	93×10^{6}	0	
Diesel	5.041×10^{12}	161.1×10^{9}	37.97×10^{9}	6.19×10^{9}	0	
Natural Gas	–	–	–	–	-	
Other Lube oil	584.84×10^{9}	18.7×10^{9}	4.06×10^{9}	717×10^{6}	0	
Other						
Sum, item (8):	5.707×10^{12}	182.23×10^{9}	42.56×10^{9}	7.00×10^{9}	0	

(6) Direct External Energy in total Btu's for each element by energy type, and as sum of each energy type for all elements.

$\Sigma = 3.803 \times 10^{12}$ Btu
incl. (790.4×10^{9}) on-site

Elements:	Elec., Off-site	Elec., On-site	Gasoline	Diesel	Natural Gas	Other	Other
Mining	0	584.5×10^{9}	358.0×10^{9}	2.379×10^{12}	0	Lub. oil 276.0×10^{9}	
Crushing	0	205.9×10^{9}	0	0	0	0	
Sum, item (6):	0	790.4×10^{9}	358.0×10^{9}	2.379×10^{12}	0	276.0×10^{9}	



(11) Resource Recovery

Resource:
99.05×10^{6} tons ~~units~~
5.5×10^{6} Btu/ton ~~unit~~
544.75×10^{12} Btu

Resource Recovery Efficiency 89.0 %

Unrecovered Resource:
14.86×10^{6} tons ~~units~~ x 5.5×10^{6} Btu/ton ~~unit~~
$= 81.72 \times 10^{12}$ Btu

(1) Principal Energy Input
Type Raw shale, 30 gal/ton
Quantity, units 84.189 $\times 10^{6}$ Tons/yr
Btu/unit: 5.5×10^{6} Btu/ton
Btu input: 463.0×10^{12}

Module Title: Shale - surface mining

(4) Process Efficiency 92 %

(2) Principal Energy Loss: 37.0×10^{12} Btu

(7) External Energy Loss: 11.860×10^{12}

(5) Principal Energy to be used with Process Boundary: 0 Btu

(3) Principal Energy output to next module, or Energy Product of trajectory if this is last module in trajectory.

Type, Physical Units:	Btu:
Raw shale, 77.454×10^{6} tons	426.0×10^{12}

FIGURE 5.8
Module Data for Illustration Trajectory: Surface Mining, Oil Shale
Scaling Factor for Standard Module 77.454×10^{6} Standard Module 4.1.1.1

It can be seen that x is 779 kwh per 1000 tons. Therefore, the annual on-site electricity requirement in item (6) is:

(779 kwh)(77.454 x 10^3)(341.3 Btu/kwh) = 205.9 x 10^9 Btu.

This is entered on the worksheet, item (6). All other items on the worksheet are calculated and written down as discussed for earlier modules

5.11 Step 11: Enter Module Data on Trajectory Worksheet

As with other modules, the data from Figure 5.8 must be entered on Figure 5.5.

At this point, it should be noted that the on-site power plant has resulted in 7.115 x 10^{12} Btu output, and the mining and raw shale conveyance modules have only required 825 x 10^9 Btu. Therefore, 6.290 x 10^{12} Btu of excess electricity must be accounted for somehow. As will be seen, some of this can be utilized for "Spent Shale Disposal".

5.12 Step 12: Calculate Spent Shale Disposal Module

Figure 5.9 is the worksheet for the "Spent Shale Disposal" module. The operations are similar to those of previous modules. It is assumed that no sensible heat or remaining carbon in the spent shale are captured and used; therefore, item (5) is zero. Since no Principal Energy is produced through this module, item (3) is zero. From Figure 5.5, it can be seen that the Principal Energy Input is zero in this case; thus, item (1) is zero. The Standard Module 4.1.4 is based on handling 1000 tons of spent shale. The scaling factor is 63.1 x 10^3 for this illustration.

For item (6), it will be assumed that all the electricity comes from the on-site power plant. This is only 789 x 10^3 Btu. Lubricating oil is assumed to have the same heating value as fuel oil, 5,838,000 Btu/Bbl.

5.13 Step 13: Enter Data on Trajectory

As with similar steps, Figure 5.5 is again utilized and module data is entered. The on-site electricity, 789 x 10^3 Btu, is shown in parentheses as it was for the surface mining and convey raw shale steps.

At this point, the energy balance of the on-site electricity generation and consumption can be calculated. Generation is 7.115 x 10^{12} Btu. Consumption is (790.4 x 10^9 + 34.1 x 10^9 + 789 x 10^3), which is a total of 824.5 x 10^9. The generation exceed the on-site consumption by 6.290 x 10^{12} Btu. In actual practice, the off-site electricity purchased for the retort could now be replaced by on-site electricity, and Figures 5.2 and 5.5 changed to indicate this. However, since this is only an illustration, the change will not be made in this case, in the interests of simplicity.

(10) Grand Total, External Energy Inputs (8)+(9): $\Sigma = 91.82 \times 10^9$ Btu

Crude Oil	Natural Gas	Coal	Hydropower	Nuclear	Other Energy
13.68×10^9	13.85×10^9	55.26×10^9	451×10^6	2.58×10^9	

(9) Energy in Materials, by type of energy, as resources in ground.

Material	Quantity, Units	Crude Oil	Natural Gas	Coal	Hydropower	Nuclear	Other Energy
Steel-Equipment	620 tons	12.06×10^9	18.65×10^9	53.58×10^9	377×10^6	2.58×10^9	
Rubber	105 "	1.57×10^9	1.16×10^9	1.66×10^9	77.2×10^6	375×10^3	
Copper	0.6 "	45.76×10^6	41.59×10^6	17.46×10^6	1.6×10^6	7.96×10^6	
	Sum, item (9):	13.67×10^9	19.85×10^9	55.26×10^9	451×10^6	2.58×10^9	

Grand Total, (9): 91.82×10^9 Btu

(8) Total External Energy as Resources in Ground:

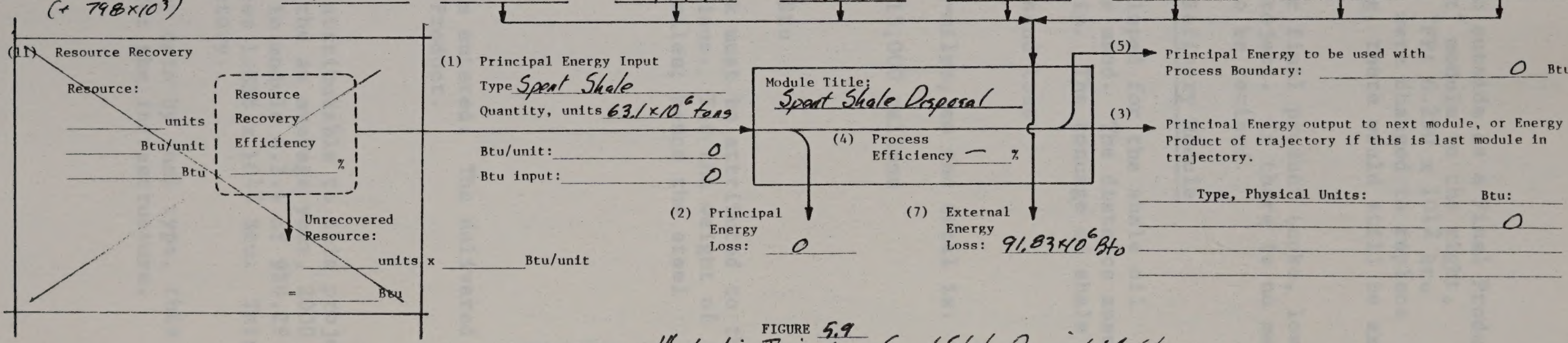
Direct Energy type:	Crude Oil	Natural Gas	Coal	Hydropower	Nuclear	Other Energy
Electric, Off-site	0	0	0	0	0	
Electric, On-site	0	0	0	0	0	
Gasoline	4.1×10^3	1×10^3	75	50	0	
Diesel	8.83×10^6	282×10^3	61×10^3	11×10^3	0	
Natural Gas						
Other						
Other						
Sum, item (8):	8.83×10^6	283×10^3	61×10^3	11×10^3	0	

Grand Total, (8): 9.189×10^6 Btu

(6) Direct External Energy in total Btu's for each element by energy type, and as sum of each energy type for all elements.

Elements:	Elec., Off-site	Elec., On-site	Gasoline	Diesel	Natural Gas	Other	Other
Haul, compact	–	–	–	4.17×10^6	–	Oil 170×10^3	
Revegetate	–	(12.5 kwh) 789×10^3	18×10^3	–	–		
Sum, item (6):	–	789×10^3	18×10^3	4.17×10^6	–	170×10^3	

$\Sigma = 4.358 \times 10^6$ Btu
$(+ 798 \times 10^3)$



~~(11) Resource Recovery~~

~~Resource:~~
~~units~~
~~Btu/unit~~
~~Btu~~

~~Resource Recovery Efficiency %~~

~~Unrecovered Resource:~~
~~units x Btu/unit~~
~~= Btu~~

(1) Principal Energy Input
Type Spent Shale
Quantity, units 63.1×10^6 tons
Btu/unit: 0
Btu input: 0

Module Title: Spent Shale Disposal

(4) Process Efficiency – %

(2) Principal Energy Loss: 0

(7) External Energy Loss: 91.83×10^6 Btu

(5) Principal Energy to be used with Process Boundary: 0 Btu

(3) Principal Energy output to next module, or Energy Product of trajectory if this is last module in trajectory.

Type, Physical Units:	Btu:
	0

FIGURE 5.9
Module Data for Illustration Trajectory: Spent Shale Disposal Module
Scaling Factor for Standard Module 63.1×10^3 Standard Module 4.1.4

The excess of on-site generation will be sold outside as a Final Product. A new arrow is drawn from the "On-site Power Plant" module to the right, crossing the boundary to the right and indicating "FP: 6.290×10^{12} Btu Electricity". (Note that, even if the trajectory were changed to replace off-site power with an on-site power for retorting, there would still be excess power available as a Final Product.)

The marketability of electricity or any other final product (coke, low-Btu gas, etc.) is a matter beyond the scope of this project. If there is no market for a product, the net energy analysis may have to be revised.

5.14 Step 14: Calculate Transport Shale Oil to Refinery Module

A new module worksheet, Figure 5.10, is developed for the shale oil transportation to the refinery. Rail transport is used. The distance assumed will be 300 miles, one-way, or 600 miles round trip. The tonnage of shale is:

$$\frac{(143{,}000\ \text{Bbl/day})(331\ \text{days/year})}{(6343\ \text{Bbl/1000 tons})} = 7462\ \text{thousand tons}$$

Diesel fuel used is 2.5 gallons per 1000 ton-miles, so the total is:

$$(2.5\ \text{gal/1000 ton-miles})(7462)(600\ \text{miles}) = 15{,}000\ \text{gallons}$$

The energy is:

$$(15{,}000\ \text{gal})(139{,}000\ \text{Btu/gal}) = 2.085 \times 10^{9}\ \text{Btu}$$

It will be assumed that 50 miles of new track must be attributed to the trajectory for the purposes of materials calculations. For the weight of trains, assume a total shipping distance of 1000 miles; hence the steel required is:

$$7.77\left(13.8 + \frac{1000}{40}\right) = 865\ \text{tons}$$

5.15 Step 15: Enter Data on Trajectory

Returning to Figure 5.5, data from Step 14 is entered. The delivered oil oil of 275.49×10^{12} Btu is the trajectory Final Product.

5.16 Step 16: Calculate Infrastructure Energy

The "full-time equivalent" (FTE) population attributable to this project must be determined. It will be assumed that for the an average year, 2000 FTE's will be required. The energy total showin in module 4.3.4 of 929.29 $\times 10^{6}$ Btu per capita, times the 2000 FTE's, produces 1.858×10^{12} Btu. This is entered on Figure 5.5 at the top of the trajectory.

If is desired to calculate overall trajectory data by fuel type, this information is available in the standard module for the infrastructure.

	Crude Oil	Natural Gas	Coal	Hydropower	Nuclear	Other Energy
(10) Grand Total, External Energy Inputs (8)+(9): $\Sigma = 65.112 \times 10^9$ Btu	$28,315 \times 10^9$	$36,042 \times 10^9$	103.16×10^9	724.3×10^6	$1,187 \times 10^9$	

(9) Energy in Materials, by type of energy, as resources in ground.

35-year life

Material	Quantity, Units	Crude Oil	Natural Gas	Coal	Hydropower	Nuclear	Other Energy
Steel track	411 tons	4.94×10^9	7.583×10^9	21.79×10^9	149.5×10^6	$.745 \times 10^9$	
Rock	3946 "	621×10^6	28.30×10^6	76.55×10^6	5.45×10^6	$37,9 \times 10^6$	
Wood	364 "	12.2×10^6	364×10^3	—	—	432×10^9	
Steel- train	865 "	18.32×10^9	28.29×10^9	81.27×10^9	563×10^6		
	Sum, item (9):	$23,897 \times 10^9$	35.901×10^9	103.13×10^9	718.9×10^6	1.187×10^9	

Grand Total, (9): 60.517×10^9 Btu

(8) Total External Energy as Resources in Ground:

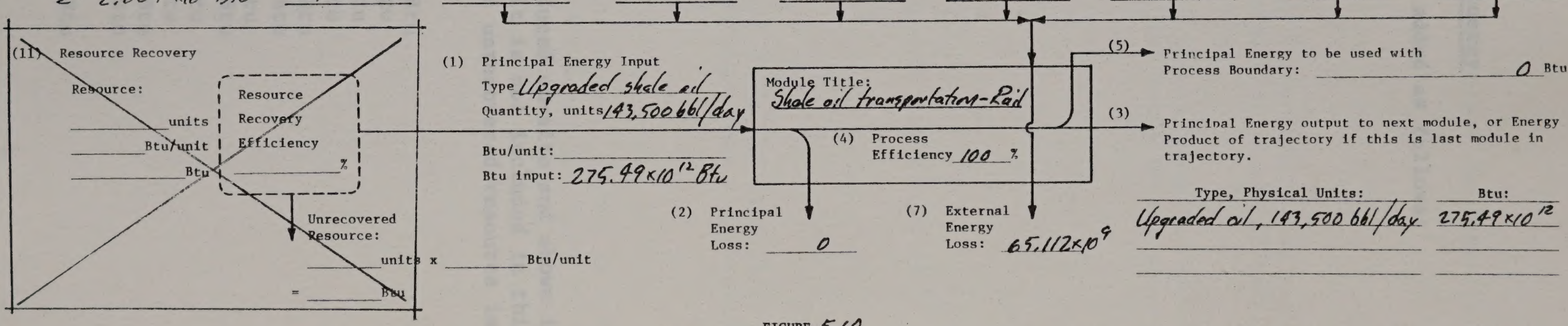
Direct Energy type:	Crude Oil	Natural Gas	Coal	Hydropower	Nuclear	Other Energy
Electric, Off-site						
Electric, On-site						
Gasoline						
Diesel	4.418×10^9	141×10^6	31×10^6	5.4×10^6		
Natural Gas						
Other						
Other						
Sum, item (8):	4.418×10^9	141×10^6	31×10^6	5.4×10^6		

Grand Total, (8): 4.595×10^9

(6) Direct External Energy in total Btu's for each element by energy type, and as sum of each energy type for all elements.

Elements:	Elec., Off-site	Elec., On-site	Gasoline	Diesel	Natural Gas	Other	Other
Rail Haul	—	—	—	2.085×10^9	—	—	
Sum, item (6):	0	0	0	2.085×10^9	0	0	0

$\Sigma = 2.085 \times 10^9$ Btu



(11) Resource Recovery

Resource: ______ units ______ Btu/unit ______ Btu

Resource Recovery Efficiency ______ %

Unrecovered Resource: ______ units x ______ Btu/unit = ______ Btu

(1) Principal Energy Input

Type Upgraded shale oil

Quantity, units 143,500 bbl/day

Btu/unit: ______

Btu input: 275.49×10^{12} Btu

Module Title: Shale oil transportation-Rail

(4) Process Efficiency 100 %

(2) Principal Energy Loss: 0

(7) External Energy Loss: 65.112×10^9

(5) Principal Energy to be used with Process Boundary: 0 Btu

(3) Principal Energy output to next module, or Energy Product of trajectory if this is last module in trajectory.

Type, Physical Units:	Btu:
Upgraded oil, 143,500 bbl/day	275.49×10^{12}

FIGURE 5.10

Module Data for Illustration Trajectory: Shale oil Transportation to Refinery Module

Scaling Factor for Standard Module 917.4 Standard Module 4.1.6

5.17 Step 17: Calculate Total Trajectory Net Energy

Figure 5.5 is now complete. Totals can be added as follows:

Final Product FP:	275.49 x 10^{12} Btu
	12.90 x 10^{12} Btu
	6.29 x 10^{12} Btu
	294.7 x 10^{12} Btu
Direct Energy DE:	11.86 x 10^{12} Btu
	3.34 x 10^{9} Btu
	2.756 x 10^{12} Btu
	50.384 x 10^{12} Btu
	2.085 x 10^{9} Btu
	65.005 x 10^{12} Btu
Total External Energy:	5.939 x 10^{12} Btu
	8.187 x 10^{12} Btu
	7.36 x 10^{9} Btu
	56.782 x 10^{12} Btu
	9.19 x 10^{6} Btu
	4.595 x 10^{9} Btu
	70.919 x 10^{12} Btu
Materials Energy:	5.921 x 10^{12} Btu
	35.4 x 10^{9} Btu
	960.6 x 10^{9} Btu
	685.4 x 10^{9} Btu
	1.445 x 10^{12} Btu
	91.82 x 10^{9} Btu
	60.52 x 10^{9} Btu
	9.202 x 10^{12} Btu
Infrastructure Energy:	1.858 x 10^{12} Btu

Total Losses include the direct energy produced on-site and shown in parentheses; this energy is indeed lost and if it is not included in this total, some energy will be unaccounted for. The unrecovered resource is included also.

Total Losses:	11.860 x 10^{12} Btu
	790.4 x 10^{9} Btu
	35.4 x 10^{9} Btu
	34.1 x 10^{9} Btu
	124.1 x 10^{12} Btu
	4.020 x 10^{12} Btu
	65.112 x 10^{9} Btu
	13.906 x 10^{12} Btu
	91.83 x 10^{9} Btu
	789. x 10^{3} Btu
	75.18 x 10^{12} Btu
	295.13 x 10^{12} Btu
Initial Principal Energy: (Resource)	544.8 x 10^{12} Btu

The net yield, using the summation accounting method for Issue 3, as shown on Figure 2.9, is:

Principal Energy	544.8×10^{12} Btu
Total Losses	295.13×10^{12} Btu
Net Yield	249.0×10^{12} Btu

This Net Yield is not the same as the Final Product due to external energy investment in direct and indirect energy, in materials, in the infrastructure, and in initial resource left in the ground.

Other calculations can be made. A relevant one is issue 1, which does not include resources in the ground. In this case, the total losses are:

Direct Energy DE:	65.01×10^{12}
Internally-produced DE:	790.4×10^{9}
	34.1×10^{9}
	789×10^{3}
	4.358×10^{6}
	65.83×10^{12}

Hence, the net energy yield for issue 1, as per Figure 2.7, is

FP:	294.7×10^{12} Btu
DE:	$- 65.83 \times 10^{12}$ Btu
Net Yield:	228.9×10^{12} Btu

Greater detail, or calculations of "critical fuels" of petroleum, can be calculated by taking data from the module worksheets. This illustration is not carried to that level of detail.

5.18 Step 18: Regional Analysis

The steps thus far have dealt with a single action. If two or more actions are proposed, then trajectories can be developed for each, and the sums of net energy yield (step 17) for each can be aggregated into a regional analysis.

6. ALTERNATIVE ENERGY SYSTEMS

6.1 INTRODUCTION

This chapter presents discussions and data on alternative energy systems for comparison or regional analysis purposes. The systems are presented in a rather general way. In several cases, very complex systems such as the nuclear fuel cycle are presented as a single module. To present this with each module discussed individually would be a task of comparable scope to the development of this entire handbook.

6.2 CRUDE OIL TO PETROLEUM PRODUCTS

Discussion of Process

The production of petroleum products from crude oil and natural gas liquids involves five discrete steps, each of which consumes energy. The entire crude oil-to-petroleum products process will be treated as a single module for this handbook. If the analyst wishes to study a different or site-specific process, the methodolgy of this handbook and the trajectory of reference (1) can be used; specific data for the oil and gas field, pipeline, and refinery will have to be obtained.

The first element in this module is exploration to locate the oil. This step can require a very large energy input per barrel of oil found, as in the case of exploring the Outer Continental Shelf, or can require a relatively small energy input per barrel of oil found, as in the case of exploring the area around a producing oil field. In either case, however, there is a real expenditure of energy that should be taken into account when performing a net energy analysis of this trajectory.

The second element in this trajectory is the actual production of crude oil. This module involves materials as well as energy expenditures for the drilling rigs, pumps, and related equipment.

The third element involves pipelining from fields to refineries.

The fourth module involves refining the petroleum into various products. In a refinery, crude oil is first distilled into four different fractions based on boiling ranges. Straight-run gasoline boils at the lowest temperatures. Straight-run distillate for kerosine, jet fuel, numbers 1 and 2 fuel oil and diesel fuel boil off at 400° F to 650° F. The next fraction is called the gas oil fraction; it boils off from 650° to 850°F, and is generally sent to a catalytic cracking unit, where it is broken into gasoline and various oils. The last fraction is used for asphalt and heavy fuels. Refineries have a variety of cracking units, reforming units, and other processes.

The data presented here are national averages rather than representing a specific refinery. First, there is no single refinery which can be considered as typical or average. Second, in any region, th petroleum products which are consumed represent a mix of crude oils from various sources, refined in refineries of various characteristics and efficiencies, and shipped various distances using a variety of transportation modes. Here, the industry-wide

data used by the Colorado Energy Research Institute (CERI), reference (1), are utilized. One important aspect of this data should be noted. The CERI study utilized data from the early 1970's. Since then, refineries have essentially achieved a 20% reduction in gross energy consumption (losses); see reference (2). Accordingly, it will be assumed that the CERI data should be modified to reflect this conservation. The CERI study shows a 0.08 x 10^6 Btu principal energy loss for a 1.00 x 10^6 Btu principal energy output for a refinery. This is now changed to a 0.06 x 10^6 Btu loss. The CERI study shows a direct energy input of 74 x 10^3 Btu and total direct plus indirect energy input of 180 x 10^3 per 1.00 x 10^6 Btu principal energy output for the refinery. These figures are now adjusted to assume a 20% reduction in energy losses (external inputs); hence, the direct energy input is now 60 x 10^3 Btu and the total direct plus indirect is 146 x 10^3 Btu. It is noted that, in the CERI data, these are not resources in the ground and are not disaggregated by energy type. The energy type disaggregation of reference (3) will be used to develop the data in table 6.1; this table then shows indirect energy as resources in the ground.

The fifth element involves petroleum product pipelining and trucking to markets.

Module Elements and Data

This entire module is summarized with the appropriate data in table 6.1. The elements of exploration and production, pipelining, refining and final pipelining and trucking are well combined into one module. There is no geographic disaggregation.

It is assumed that the entire energy input to the refinery, both Principal Energy and all external energies, are distributed between all products as a proration of an average product slate. This is not technically accurate, as it takes additional steps and energy in a refinery to produce the lighter fractions or larger quantities of them.

However, every refinery produces a mix of products due to national demand and the intrinsic characteristics of oil and refining in general. The scope of this study does not permit detailed analysis of refining to try to arrive at some breakdown of energy by product from a refinery, and no data have been located which present this breakdown.

TABLE 6.1

Module: Crude Oil to Petroleum Products

Element 1: Crude oil to petroleum products

(a) Equipment, facilities

Exploration trucks, seismic equipment, office equipment
Drilling rigs
Pumps, tanks
Pipelines, pumping stations
Refineries
Tank farms
Trucks, barges, tanker vessels

(b) Assumptions

(1) CERI trajectory from reference (1), page II-10, utilized as this module.
(2) U.S. average data
(3) 1972 data from CERI study, reference 1, updated to reflect 20% conservation of principal energy used internally in refining and external energy purchased for refining.
(4) Energy inputs into refinery equally distributed to all products; no attempt made to distinguish the net energy of each product of refinery.
(5) No geographic disaggregation is made.
(6) Materials energy calculated from reference (1), which was based on economic, not physical, data of materials purchased.
(7) Pipeline length to refinery and from refinery to market is 300 miles; truck distribution is 70 miles.

(c) Guidelines on data

(1) Data are directly comparable to a trajectory of this handbook.

(d) Data

For Final Product of $1.00 \text{ x } 10^{6}$ Btu:

Step	Principal Energy Input	Principal Energy Loss	External Energy D	External Energy D + 1	Materials Energy D + 1
Exploration & Production:					
Resources in Ground	$3.27\text{x}10^{6}$				
Well output	$1.09\text{x}10^{6}$	$2.18\text{x}10^{6}$*	$7.7\text{x}10^{3}$	$18.7\text{x}10^{3}$	$11.7\text{x}10^{3}$
Pipeline	$1.09\text{x}10^{6}$	$0.03\text{x}10^{6}$	$1.0\text{x}10^{3}$	$2.39\text{x}10^{3}$	$0.7\text{x}10^{3}$
Refinery	$1.06\text{x}10^{6}$	$0.06\text{x}10^{6}$	$49.7\text{x}10^{3}$	$121.2\text{x}10^{3}$	$12.6\text{x}10^{3}$
Pipeline	$1.00\text{x}10^{6}$	0	$1.20\text{x}10^{3}$	$2.93\text{x}10^{3}$	$0.6\text{x}10^{3}$
Truck	$1.00\text{x}10^{6}$	0	$1.9\text{x}10^{3}$	$4.64\text{x}10^{3}$	$0.3\text{x}10^{3}$
Totals		$2.27\text{x}10^{6}$	$61.9\text{x}10^{3}$	$149.9\text{x}10^{3}$	$25.9\text{x}10^{3}$

TABLE 6.1 (Continued)

Step	Principal Energy Input	Principal Energy Loss	External Energy D	External Energy D + 1	Materials Energy D + 1
Totals		2.27×10^{6}	61.9×10^{3}	149.9×10^{3}	25.9×10^{3}
Fuel Mix, Resources in ground:					
Crude oil		2.27×10^{6}	18.8×10^{3}	45.9×10^{3}	7.9×10^{3}
Natural gas		0	11.0×10^{3}	26.8×10^{3}	4.6×10^{3}
Coal		0	22.9×10^{3}	55.9×10^{3}	9.7×10^{3}
Hydro		0	1.0×10^{3}	2.4×10^{3}	0.4×10^{3}
Nuclear		0	7.8×10^{3}	18.9×10^{3}	3.2×10^{3}

* Resources unrecovered

Module Energy Summary

(1) Principal Energy Input
Type: Crude Oil in Ground
Quantity, units: 0.563 Bbl
Btu/unit: 5,800,000 Btu/Bbl
Btu input: 3.27×10^{6} Btu

(2) Principal Energy Loss
2.27×10^{6} Btu

(3) Principal Energy Out
1.00×10^{12} Btu petroleum products

(4) Process Efficiency
30.6%

(5) Principal Energy Used within Process boundary:
None (use of petroleum recycled within module has been accounted for in calculations.)

(e) Data sources

(1) Melcher, A.G., and others, 1976, Net energy analysis--An energy balance study of fossil fuel resources: Golden, Colorado, The Colorado Energy Research Institute.

(2) Bodine, J. Frank and Vitullo, Marshall, 1980; Industrial energy use data book, Oak Ridge, Tennessee, Oak Ridge Associated University.

(3) Frabetti, Alton J. Jr., et al, 1975; A study to develop energy estimates of merit for selected fuel technologies, East Sundwich, Massachusetts, Development Sciences, Inc.

(4) Wolsky, A.M. and Gaines, L.L., 1981; Energy and materials flows in petroleum refining, Argonne, Illinois, Argonne National Laboratories.

(5) The MITRE Corporation, 1970; Environmental data for energy technolgoy policy analysis; McLean, Virginia, The MITRE Corporation.

(6) Hayden, J.E. and Levers, W.H., 1973; How to conserve energy while building, expanding a refinery; The Oil and Gas Journal, May 21, 1973, pages 109-116.

6.3 ELECTRICAL POWER GENERATION FROM FOSSIL FUELS

Discussion of Process

Electricity may be generated from fossil fuels (as opposed to nuclear fuels) by a variety of processes, some that have been well demonstrated at a commercial scale and some that are still highly speculative. The fuels for these processes may be solid, primarily coal; liquid, primarily various types of oil; or gaseous, primarily natural gas. The technologies for electricity generation from fossil fuels include conventional steam boiler/turbine plants, combustion turbines, fluidized-bed combustion, combined cycle, fuel cells, and magentohydrogynamics (MHD). These technologies all convert some form of fossil energy (solid, liquid, or gas) into a more useful form, electricity, that can be easily transported and used. Additionally, electricity can be generated from nuclear power plants, solar-powered facilities, wind-powered facilities, hydroelectric plants, and geothermal plants.

Electricity generation from fossil fuels is treated as a single module with three elements. This module utilizes a conventional steam boiler/turbine plant because they comprise the vast majority of electrical power generating facilities in the United States. Additionally, Federal legislation all but prohibits new power plants from using oil or natural gas as a fuel. Therefore, this module will describe a coal-fired plant and other fuels will only be briefly discussed. Several methods can be used to feed coal into a boiler including pulverized coal injection and several types of mechanical stokers. However, large utility boilers almost exclusively use pulverized coal injection which is the method assumed for this module. The three elements to this module are: 1) the boiler and system generation system; 2) the turbine, steam condenser, and generator; and 3) the flue gas treatment facility.

Module Elements and Data

For a pulverized coal-fired boiler, the coal is crushed very finely, is heated, and is blown by air into the boiler cavity through burners. The cavity of the boiler is essentially a rectangular box that may be as large as 160 ft high, 90 ft long, and 45 ft wide. In the cavity, the coal burns at temperatures approaching 300°F in huge flames that nearly fill the lower one-half of the cavity. The heat from these flames is transferred to water that boils at high pressures inside tubes (pipes) located in the boiler cavity.

From the boiler tubes, the steam/water mixture flows to a steam drum where the water is separated and returned to the boiler. The high-pressure steam flows to superheat tubes where the temperature of the steam is increased to approximately 1000°F. This superheated steam can now be used to turn turbines and generate electricity. Finally, the steam is condensed into liquid water and is pumped back to the boiler tubes. Additional energy efficiencies are achieved by using the hot flue gases from the boiler to preheat the feed water in a bank of tubes called an economizer. The hot flue gases are further utilized to preheat the combustion air to the boiler.

The primary difference for oil- and natural gas-fired boilers is relatively minor modifications to the design of the burners. Also, coal-fired boilers utilize wall blowers and soot blowers to minimize slag and ash deposits

on the boiler tubes. However, all boiler/steam systems are similar whether they are coal-, gas-, or oil-fired.

Energy losses from the boiler per se are relatively small, hence the overall efficiency of most utility boilers is 85% to 90%. The major losses from the boiler arise from incomplete combustion of the coal, heating the moisture in the coal and combustion air, and energy lost due to venting the hot flue gases.

The second element in the module, the steam turbine and generator, are exactly the same for all types of fuel. A turbine consists of sets of curved blades mounted on a shaft that rotates inside a stationary housing. The energy of the high-temperature, high-pressure steam is converted to mechanical energy (shaft rotation) by allowing the steam to impinge on the turbine blades. In actual practice, a turbine normally consists of several units that utilize the steam at various pressures. The steam is exhausted from the turbine at a relatively low temperature and pressure. Depending on the temperatures of the inlet and exhaust steam, the maximum theoretical efficiency of the turbine is approximately 64%. However, the actual efficiency of a steam turbine is 45% to 50% due to a number energy losses such as steam leakage, friction, and radiation of heat.

The waste heat from the turbine, in the form of low pressure exhaust steam, is dissipated to the atmosphere from the steam condenser. In the condenser, the heat is transferred to a cooling medium, usually water, that is maintained at a relatively cool temperature. The cooling water temperature can be maintained by the use of a wet cooling tower in which a portion of the the water is evaporated, thus lowering the temperature. An alternate method is to use a dry cooling tower in which the cooling water is passed through an air-cooled exchanger, much like an automobile radiator.

The rotating shaft of the turbine is connected to an electrical generator which converts the mechanical energy (shaft rotation) into electrical energy. A generator relies on the phenomenon that a voltage will develop in an electrical conductor when it is passed through a magnetic field. Large generators are very efficient and are capable of converting 96% to 99% of the input energy into electricity.

Lastly, the third element of the module is the gas cleanup facility that primarily removes particulates and sulfur oxides (SO_x) from the flue gases exiting the boiler. If the boiler is coal-fired (as is assumed for this module) both SO_x and particulates must be removed from the flue gases; if oil-fired, only SO_x need be removed; and if natural gas-fired, the flue gases will require essentially no flue gas cleanup facility.

Particulate removal can be accomplished with four basic technologies: cyclones, electrostatic precipitators, filter fabric baghouses, and wet scrubbers. Each type of system has its own relative merits and disadvantages. Cyclones are simple and low in cost (both capital and operating costs), but are not as efficient as other methods. Electrostatic precipitators are very effective for removing fly ash from high-sulfur coals, but are relatively high in capital and operating costs and are significantly less effective (or more expensive) for low-sulfur coals. Baghouses are very effective for all types of coal, but are high in capital cost and may prove to be quite high in operating costs. Lastly, wet scrubbers are also high in capital and operating cost and

are generally not used for large utility boilers. The selection of which method is used for particulate removal is very site specific and, therefore, no "typical" installations can be defined. However, this module assumes baghouses will be used because they are very efficient for Western coals that contain relatively low concentrations of sulfur and can also be used for high-sulfur coals. Facilities to control particulate emissions are generally not required for oil- or natural gas-fired boilers.

Energy consumption for particulate removal occurs from one of two possible sources. Either electricity must be used to operate an electrostatic precipitator or power must be expended to force the flue gases through a baghouse or cyclone. However, this internal energy use is relatively small, amounting to less than 0.5% of the total energy input to the module.

The other primary pollutants that must be removed from boiler flue gases are sulfur oxides (SO_x) that are produced from sulfur-containing compounds is the fuel. One method of control is to remove the sulfur compounds before the fuel is burned. However, most utilities choose to burn the fuel and then remove the SO_x from the flue gases by a process known as flue-gas desulfurization (FGD). Several different FGD methods are available including: 1) lime or limestone scrubbing, 2) double alkali (sodium sulfite) scrubbing, 3) sodium scrubbing (Wellman-Lord process) and 4) magnesium oxide scrubbing. The first two processes produce a sludge that must be disposed of as a waste. Whereas the second two produce a marketable by-product and the scrubbing solution is regenerated and reused. For this module, a lime/limestone process is assumed to be used because it is presently the dominant technology for FGD in the United States. If the fuel for a power plant is natural gas, FGD is not required. However, most fuel oils contain sulfur compounds, hence oil-fired boilers generally require that a FGD process be used.

The internal energy consumption for flue-gas desulfurization by the different processes is variable. However, various literature sources report that 2% to 7% of the total energy into the module must be expended for FGD. Some of this energy consumption is due to electricity that is used to power equipment. Additionally, thermal energy is required to reheat the flue gases that have been cooled in the scrubbers and have, therefore, lost the buoyancy needed to vent them up the stack.

The assumptions and appropriate data for this module are presented in Table 6.2. These data are only for a "typical" pulverized coal-fired boiler/steam turbine facility. Therefore, the data should be used only as an example of the methodology to be used for net energy analysis of an electrical power generating facility. For proper evaluation of a particular project, specific data from the developer should be used.

TABLE 6.2

Module: Electricity Generation with a Coal-Fired Steam Boiler/Turbine Plant

Element 1: Boiler and Steam System

(a) Equipment, Facilities:

The principal components are:

- Coal storage
- Boiler
- Steam drum
- Water treatment plant
- Buildings

These systems are comprised of many components including conveyors, vessels, heat exchangers, blowers, pumps, motors, piping, valves, structural steel, concrete, instrumentation, and many others.

(b) Assumptions

(1) Energy usage is based on a power plant generating 500 Mwe (net) for 292 days per year.
(2) The power plant is assumed to be a steam boiler/turbine facility.
(3) Fuel for the boiler is assumed to be pulverized coal with a heating valve of 10,500 Btu/lb and a sulfur content of 0.7%.
(4) The boiler efficiency is assumed to be 12.5%.
(5) Approximately 2.3% of the gross electricity output is used internally.
(6) Annual fuel oil consumption for boiler startup is assumed to be 42,000 gal/yr.
(7) The energy content of the water treatment chemicals (lime, soda, sulfuric acid, chlorine, etc.) is assumed to be negligible.
(8) The following energy values were assumed:
electricity = 3413 Btu/kwh
fuel oil = 139,000 Btu/gal
coal = 10,500 Btu/lb
(9) Any energy that is required to supply coal, water, chemicals, etc., is not included in the module.
(10) Transmission of the electricity is not included in the module.
(11) No economies or diseconomies of scale were assumed.

(c) Guidelines on data:

(1) Data are for a steam boiler/turbine facility fueled by pulverized coal.
(2) If the technology and coal are not changed, data may be multiplied by a linear factor based on net megawatt generation capacity relative to 500 Mw.

TABLE 6.2 (Continued)

(d) Data:

(1) Direct energy per 500 Mw net:
Fuel oil = 42,000 gal per year = 1.1 x 106 Btu/hr

(2) Material:
steam boiler steel = 7500 tons
structural and reinforcing steel = 7210 tons
concrete = 52320 tons
asphalt = 84660 tons
mechanical equipment steel = 1190 tons
electrical equipment steel = 2390 tons
pipe and hnagers steel = 1190 tons
material handling equipment steel = 1670 tons
rubber = 140 tons

(3) Losses:
Energy losses within this element arise primarily from incomplete combustion of the coal, heating the moisture in the coal and the combustion air, and venting hot flue gases. Additionally, electricity is used internally.

(e) Data sources:

(1) Energy and Environmental Analysis, Inc., 1979; A net energy analysis of various strategies for the clean use of coal: Arlington, Va., Energy and Environmental Analysis Inc., 32 p.
(2) Frabetti, Alton J., Jr., et. al., 1975; A study to develop energy estimates of merit for selected fuel technologies: East Sandwich, Massachusetts, Development Sciences Inc., 376 p.
(3) Hoffman, Lawrence, Noren, Stephen E., and Holt, Elmer C., Jr., 1980, Environmental, operational, and economic aspects of thirteen selected energy technologies: Silver Spring, Maryland, The Hoffman-Muntner Corporation, 222 p.
(4) private communications with a major engineering company

Element 2: Steam Turbine, Generator, and Condenser

(a) Equipment, Facilities:

Steam turbine
Electricity generator
Steam condensers
Cooling tower
(buildings are included in Element 1)

These systems are comprised of many components including turbines, generators, heat exchangers, pumps, motors, piping, valves, structural steel, concrete, instrumentation, and many others.

TABLE 6.2 (Continued)

(b) Assumptions:

(1) Energy usage is based on a power plant generating 500 Mwe (net) for 292 days per year.
(2) The power plant is assumed to be a steam boiler/turbine facility.
(3) The turbine efficiency is assumed to be 45%.
(4) Waste heat from the turbine is assumed to be dissipated in condensers that are supplied with cooling water from a wet cooling tower.
(5) The generator efficiency is assumed to be 97%.
(6) Approximately 0.9% of the gross electricity output is used internally.
(7) Electricity is valued at 3413 Btu/Kwh.
(8) Transmission of the electricity is not included in the module.
(9) No economies or diseconomies of scale were assumed.

(c) Guidelines on data:

(1) Data are for a steam boiler/turbine facility.
(2) If the technology is not changed, data may be multiplied by a linear factor based on net megawatt generation capacity relative to 500 Mw.

(d) Data:

(1) Direct energy per 500 Mw net.
No direct energy is consumed by this element.
(2) Material:
turbine and generator steel = 1230 tons
structural and reinforcing steel = 4320 tons
concrete = 31,390 tons
asphalt = 50,800 tons
mechanical equipment steel = 720 tons
electrical equipment steel = 1430 tons
pipe and hangers steel = 720 tons
material handling equipment steel = 1000 tons
rubber = 90 tons
(3) Losses:

Energy losses within this element arise from the inefficiencies of the steam turbine and the electrical generator. The maximum theoretical efficiency of a turbine is 64%, but actual efficiencies are lower due to steam leakage, friction losses, and heat radiation. Approximately one-half of the principal energy is lost to the environment due to the inefficiency of the steam turbine.

TABLE 6.2 (Continued)

(e) Data sources:

(1) Energy and Environmental Analysis, Inc., 1979; A net energy analysis of various strategies for the clean use of coal: Arlington, Va., Energy and Environmental Analysis Inc., 32 p.
(2) Frabetti, Alton J., Jr., et. al., 1975; A study to develop energy estimates of merit for selected fuel technologies: East Sandwich, Massachusetts, Development Sciences Inc., 376 p.
(3) Hoffman, Lawrence, Noren, Stephen E., and Holt, Elmer C., Jr., 1980, Environmental, operational, and economic aspects of thirteen selected energy technologies: Silver Spring, Maryland, The Hoffman-Muntner Corporation, 222 p.
(4) private communications with a major engineering company

Element 3:

(a) Equipment, Facilities:

The principal components are:

Filter fabric baghouse
Lime/limestone flue gas desulfurization
Sludge disposal
Vent stack
(buildings are included in Element 1)

These systems are comprised of many components including vessels, heat exchangers, pumps, motors, piping, valves, structural steel, concrete, instrumentation, and many others.

(b) Assumptions:

(1) Energy usage is based on a power plant generating 500 Mwe (net) for 292 days per year.
(2) The power plant is assumed to be a steam boiler/turbine facility.
(3) Fuel for the boiler is assumed to be pulverized coal with a heating value of 10,500 Btu/lb and a sulfur content of 0.7%.
(4) Filter fabric baghouses are assumed to be used for particulate emissions control.
(5) A lime/limestone facility is assumed to be used for flue gas desulfurization (FGD).
(6) Approximately 2% of the principal energy input to the module is assumed to be used for particulate emission control and FGD.
(7) The following energy values were assumed:
electricity = 3413 Btu/Kwh
limestone = 80,000 Btu/ton
(8) Transmission of the electricity is not included in the module.
(9) No economies or diseconomies of scale were assumed.

TABLE 6.2 (Continued)

(c) Guidelines on data:

(1) Data are for a steam boiler/turbine facility fueled by pulverized coal.
(2) If the technology and coal are not changed, data may be multiplied by a linear factor based on net megawatt generation capacity relative to 500 Mw.

(d) Data:

(1) Direct energy per 500 Mw net:
No direct energy is consumed by this element.
(2) Material:
baghouse and scrubber steel = 5800 tons
structural and reinforcing steel = 9060
concrete = 65,780 tons
asphalt = 106,430 tons
mechanical equipment steel = 1500 tons
electrical equipment steel = 3000 tons
pipe and hangers steel = 1500 tons
materials handling equipment steel = 2100 tons
rubber = 180 tons

limestone = 1.9 x 10^4 ton/yr
(3) Losses:
Electricity is used internally within this element to power equipment. Additionally, thermal energy is required to reheat the flue gas that are cooled in the FGD scrubbers and, therefore, have lost the buoyancy needed to vent them out the stack.

(e) Data sources:

(1) Energy and Environmental Analysis, Inc., 1979; A net energy analysis of various strategies for the clean use of coal: Arlington, Va., Energy and Environmental Analysis Inc., 32 p.
(2) Frabetti, Alton J., Jr., et. al., 1975; A study to develop energy estimates of merit for selected fuel technologies: East Sandwich, Massachusetts, Development Sciences Inc., 376 p.
(3) Hoffman, Lawrence, Noren, Stephen E., and Holt, Elmer C., Jr., 1980, Environmental, operational, and economic aspects of thirteen selected energy technologies: Silver Spring, Maryland, The Hoffman-Muntner Corporation, 222 p.
(4) private communications with a major engineering company

TABLE 6.2 (Continued)

Module Energy Summary

(1) Principal Energy Input
Type: Coal
Quantity, units: 232.1 ton/hr
Btu/unit: 10,500 Btu/lb
Btu input: 4874.6 x 10^6 Btu/hr
(2) Principal Energy Loss
3168.5 x 10^6 Btu/M
(3) Principal Energy Output
Type: Electricity
Quantity: 1706.1 Btu/M
(4) Process Efficiency
35.0%
(5) Principal Energy Used within Process Boundary:
Assumed to be none, but electricity is available.

(a) Materials Summary, All 3 Elements

Boiler Steel	7,500 tons
Structural Steel	30,590 tons
Concrete	149,490 tons
Asphalt	241,890 tons
Mechanical Steel	4,640 tons
Electrical Steel	6,820 tons
Pipe and Hanger Steel	3,410 tons
Material Handling Steel	4,770 tons
Rubber	410 tons
Baghouse Steel	5,800 tons
Limestone	19,000 TPY

6.4 NATURAL GAS

Discussion of Process

The provision of natural gas at the marketplace commences with exploration for and discovery of gas. Exploration requires field work, with sophiticated seismic exploration techniques, and office analysis of well logs, geologic maps, geologic cross sections and other data. If a prospect of liquid or gaseous hydrocarbons is identified, the next step is drilling an exploratory well. If hydrocarbons are found, the well becomes a producing well; additional development wells are usually drilled. The hydrocarbons may be primarily liquid (crude oil and liquid petroleum and natural gases) or gas; crude oil and gas may be "associate" (produced from the same well) or the gas may be produced from a well without crude oil, as either "dry gas" or "wet gas" containing natural gas liquids. As of the end of 1978, about two-thirds of the nation's reserves of natural gas were non-associated.

An economically productive field must be developed, and a gathering system must be installed, as the next part of the process. For associated gas, a gas-oil separator is installed at each well. Typically, the gas is taken to a gas liquids plant wehre the gas is dried and liquids are extracted before the gas is pressurized and introduced into a pipeline for transmission. Repressuring is necessary at intervals along the pipeline. Energy for repressuring comes entirely from pipeline gas; hence, no direct external energy is used. It is sometimes necessary to add a hydrogen sulfide removal process at the gas liquids plant if the gas is "sour", i.e., contains significant quantities of hydrogen sulfide.

Module Elements and Data

The module discussed here consists of two elements: (1) exploration, drilling, gathering, and gas liquids separation, and (2) pipeline transmission. Data for the first element is presented on a basis of mcf (or Btu's) of gas. Data for the second element are presented on the basis of mcf and pipeline length. Western regional average data from reference 1 are used. A specific load center, or a specific pipeline, will deviate somewhat from this average data. However, it is not realistic in this handbook to identify all the specific deviations which might occur. The data which follow on Table 6.3 assume that no sour gas plant is incorporated into the system.

The entire data here, and the assumptions and procedures, are those of reference (1); the reader is referred to pages VI-21 through VI-47 for a complete discussion of methods and assumptions.

TABLE 6.3

Module: Natural Gas System

Element 1: Exploration, Production, Gathering, and Natural Gas Liquids Plant

(a) Equipment, facilities

Drilling rig
Casing
Well-head valves, gauges
Gathering field pipes
Natural Gas Liquids Plant
    Machinery and control equipment
    Structural, tank and pipe steel
    Concrete
    Miscellaneous glass, paving, etc.
Contract construction equipment and energy

(b) Assumptions

(1) New gas and oil exploration and production, not existing.
(2) Overall average data, not site-specific.
(3) Energy inputs prorated between gas and oil (whether associated or not) on a Btu-of-product basis.

(c) Guidelines on data

(1) Data must be multiplied by ratio of actual Btu to 1 x 10^6 Btu to develop data for actual module.

(d) Data

(1) Direct energy per million Btu (1 x 10^6 Btu) output of gas liquid plant into pipeline:
    Electricity: 1.15 x 10^3 Btu
    Natural Gas: 5.08 x 10^3 Btu
(2) Materials per 1 x 10^6 Btu output:
    A breakdown by type of material is not available. A total materials energy input is the only available data; this is 14.0 x 10^3 Btu

Element 2: Pipeline

(a) Equipment, facilities

Pipe
Compressors, motors
Concrete, structural steel, building materials
Contract construction: excavation, pipelaying, etc.

TABLE 6.3

Continued

(b) Assumptions:

(1) Same as Element 1
(2) Pipeline length = 1000 miles

(c) Guidelines on data:

(1) Data must be multiplied by:

- ratio of actual Btu to 1 x 10^6 Btu
- ratio of actual pipeline length to 1000 miles

(d) Data

(1) Direct energy per million Btu (1 x 10^6 Btu) delivered from 1000-mile pipeline.

Electricity = 0
Natural Gas = 0
Petroleum Products = 0

Materials energy per million Btu (1 x 10^6) delivered from 1000-mile pipeline: Total (see Element 1) is 16.9 x 10^3 Btu.

References:

(1) Melcher, Albert G. et al, 1976, Net energy analysis: an energy balance of fossil fuel resources; Golden, Colorado, Colorado Energy Research Institute.

6.5 URANIUM TO ELECTRICITY

Discussion of Process

The production of electricity from nuclear energy is a sufficiently complex subject that a handbook several times the size of this would be required to cover it in detail. For this handbook, it will be treated as a single module, and national average data will be presented.

The entire nuclear fuel cycle consists of a mix of trajectories with the following major steps and options within each step:

- Uranium Mining
  - Open pit
  - Underground
  - In situ leaching
  - Heap leaching

- Uranium Milling to produce U_3O_8, "yellowcake"
  - Acid leach
  - Alkaline leach
  - Solvent extraction

- Yellowcake transportation

- Uranium Hexafluoride Production

- Uranium Enrichment
  - Gaseous diffusion
  - Gas centrifuge (planned)

- Fuel Fabrication

- Transportation to reactors (truck, rail, barge)

- Power Generation
  - Light water reactor
  - High temperature gas cooled reactor

- Fuel Reprocessing

- Waste Handling
  - Low-level
  - High-level
    - Permanent Repository (planned)
    - Vitrification (planned)

There are a number of variables in each step. For example, economics (yellowcake price) and technologies determine the resource recovery in mining and milling. Political factors affect fuel reprocessing.

In uranium milling to produce "yellowcake", the ore is finely crushed and pulverized, and the uranium is dissolved out of the ore by chemical reagents. The process is called "leaching", and can be done with either acids or alkine

chemicals, depending on the chemistry of the ore. From the leaching fluid, the dissolved uranium is extracted by solvent extraction or ion exchange techniques. The excess water is removed and the product is a dried uranium oxide concentrate called "yellowcake."

This concentrate is shipped to a uranium hexafluoride conversion plant, where in a complex series of steps, the uranium oxide is converted to a gas called uranium hexafluoride (UF_6). There are two plants in the U.S. which process the uranium to hexafluoride, which is then shipped to an enrichment plant. There are three of these in the U.S. Here, the ratio of U_{235} to U_{238} is changed by diffusing the gaseous hexafluoride through membranes. The concentration of U_{235} is increased from less than one percent to about three or four percent.

Finally, the enriched gas is converted into solid uranium, uranium dioxide, or uranium carbide. These materials are then fabricated into small pellets which are placed in rods.

The rods are then shipped to nuclear reactors. In place in the reactor, the uranium atoms split (fission), releasing heat and forming new elements such as plutonium. The heat is transferred to water or helium, which in turn transfers the heat through a heat exchanger to a secondary water loop; the water is boiled to steam in the exchanger. The steam then drives a turbine and generator as in a fossil-fuel-fired power plant.

Module Elements and Data

The entire nuclear fuel cycle is treated as one module.

Data for the entire module are presented in Table 6.4. This table is taken from reference (1), and represents a typical 100 Mw light water reactor with U.S. average data for mining, milling, etc. The data are disaggregated by fuel type in the table, using other tables on nuclear net energy in reference (1).

The approach used by investigators of reference (1) is almost identical to that used by the Colorado Energy Research Institute and by the authors of this handbook; hence, the data from reference (1) are consistent and compatible with the data generated for this study. Some terminology in reference (1) is slightly different; for example, reference (1) refers to "in situ resources" rather than resources in the ground." Energy disaggregation by fuel type is available for each operation in reference (1).

Geographic disaggregation of the data of Table 6.4 poses a significant problem. The uranium mining and milling is done in various places, primarily in the western U.S., for example. The operating energy for the module could be split up as shown in Table 6.4, and assumptions could be made as to the location of each activity listed. The infrastructure energy can be calculated for the assumed geographic regions, using the data in the table, which are taken from reference (2). Note that it is presented for 1 x 10^{12} Btu output of electricity.

TABLE 6.4

Module: Uranium to Electricity

Element 1: Nuclear Fuel Cycle

(a) Equipment, facilities

See text

(b) Assumptions

(1) Average 1000 Mw light water reactor.
(2) U.S. average data on all aspects and operations of nuclear fuel cycle.
(3) For specific details, see reference (1).

(c) Guidelines on data

(1) Data are directly comparable to a trajectory of the handbook.
(2) Geographic disaggregation: see text.
(3) Infrastructure assignment to geographic areas: see text.

(d) Data

Note: "Remaining Resource" indicates the usable Principal Energy in the trajectory after each step; the different between each number and the preceeding number represents the loss of Principal Energy in the particular step.

(1) Total Energy and Materials Energy per million Btu (1 x 10^6 Btu or 293 kwh), as resources in the ground.

Pathway Step	Resource Remaining (Btu)	External Energy Inputs (10^6 Btu)		
		Operating (Direct & Indirect)	Material	Total
Research and Development	(start) 5,821 x 10^9	3,071	--	3,071
Exploration	--	659	--	659
Mining	5,531 x 10^9	237	92	329
Milling	5,254 x 10^9	4,764	212	4,976
UF_6 Production	5,245 x 10^9	1,759	42	1,801
UF_6 Enrichment	4,515 x 10^9	166,116	255	166,371

TABLE 6.4

Continued

Pathway Step	Resource Remaining (Btu)	External Energy Inputs (10^6 Btu)		
		Operating (Direct & Indirect)	Material	Total
Fuel Fabrication	4,474 x 10^9	1,535	403	1,938
Power Plant	1,000 x 10^9	31,774	19,433	51,207
Spent Fuel Processing	--	1,281	859	2,140
Transportation	--	0,156	--	156
Land Reclamation	--	175	--	175
TOTAL		211,527	21,296	232,823

Fuel Type (10^6 Btu) of External Energy Inputs:

	Operating	Material	Total
Coal	91,605	6,611	98,216
Oil and Gas	85,652	13,348	99,000
Hydro & Nuclear	34,270	1,337	35,607

(2) Infrastructure Energy: personnel per operation, per million million Btu (1 x 10^{12} Btu, or 293,000 kwh)

Operation	Workers Construction, time	Operations
Uranium Open pit mining	1.0 (4 yrs)	3.5
Uranium Underground mining	1.1 (3 yrs)	12.3
Uranium milling	0.7 (2.3 yrs)	2.7
Light Water Reactor	29.0 (9 yrs)	5.7
Fuel Reprocessing Plant	1.5 (6 yrs)	0.7

Source: reference (2)

References:

(1) Frabetti, Alton J. Jr., et al, 1975, A study to develop energy estimates of merit for selected fuel technologies; East Sandwich, Mass., Development Sciences, Inc.

TABLE 6.4

Continued

(2) The MITRE Corporation, 1979, Environmental data for energy technology policy and analysis, volume 1: Summary; McLean, Virginia, The MITRE Corporation.

(3) Rotty, Ralph M., Perry, A.M., and Reister, David B., 1975, Net energy from nuclear power; Oak Ridge, Tennessee, The Institute for Energy Analysis, Oak Ridge Associated Universities.

(4) Schatz, Joel, et. al., 1975, Transition; Portland, Oregon, Office of Energy Research and Planning, Office of the Governor, State of Oregon.

(5) Loftness, Robert L, D. Sc., 1978, Energy handbook; New York, Van Nostrand Reinhold Company.

Module Energy Summary for nuclear power plant, per 45.5 Mw of generating capacity at 75% capacity factor.

(1) Principal Energy Input
    Type: Uranium ore in ground, 0.3% recoverable U_3O_8
    Quantity, units: 626.9 tons
    Btu/unit: 9.286×10^9 Btu per ton
    Btu input: 5.82×10^{26} Btu per year
(2) Principal Energy Loss
    4.82×10^{12} Btu per year
(3) Principal Energy Output
    Type: electricity from power plant
    Quantity: 1.00×10^{12} Btu per year
(4) Process Efficiency
    17.2%
(5) Principal energy to be used within process boundary:
    None.

6.6 COAL

This section is subdivided into a number of modules.

6.6.1 Coal Mining

Many techniques are available by which coal may be removed from the ground for useful applications. The two major classifications of coal mining are underground and surface mining. Since each of these classifications is characterized by unique levels of energy consumption, they will be discussed separately in the following section.

6.6.1a Underground Coal Mining

Discussion of Process

Underground coal mining can be divided into several mining methods, including conventional room-and-pillar mining, continuous room-and-pillar mining, longwall mining, and shortwall mining. Each of these methods exhibits certain advantages and disadvantages relative to the others, and each is suitable for use under a specific set of topographic, geologic, and economic conditions.

Conventional room and pillar coal mining is the dominant underground method being used in the United States today. However, it is gradually being replaced by continuous room and pillar mining because of time and manpower savings that can be realized as a result of this second method. For this reason, continuous room and pillar mining is the method that has been selected to represent underground coal mining in this handbook.

Continuous mining utilizes a single machine to tear the coal from the face of the coal seam being mined. The term "continuous" stems from the fact that this single machine replaces three machines used in conventional mining that performed their functions on a cycled, or batch, basis. The most popular type of continuous miner is a "ripper" machine with three or four cutting wheels mounted on the same level and turning in vertical planes on arms that can be raised, lowered, and turned sideways. The wheels are studded with cutting teeth to rip out the coal. All continuous miners are crawler-mounted and have ramp-type loaders built into them. These loaders are used to load the coal onto shuttle cars for transport to a larger conveyor belt that carries the coal to the surface.

Once mining is completed in a given area, roof bolts from 4 to 8 ft. in length are placed in the mine roof. The effect of the bolting is to provide support for chunks of rock that might otherwise fall, to strengthen the roof, and to tie the flat, comparatively weak arch to a higher, more competent one above. Roof-bolting machines are commonly wheel-mounted for easy movement.

Once on the surface, the run-of-mine (ROM) coal can be prepared for transport to market by any number of standard techniques. For the sake of brevity only, two coal preparation processes will be included in this handbook.

In the first and most limited process, the coal is crushed to the desired size in one or more crushers before being conveyed to a stockpile. Items such as a dust extraction system, belt weighers, tramp iron magnets, and dust suppression are included, but there is no washing of the coal before being transported to market.

In the second coal preparation process, the ROM is conveyed to a breaker in which large rocks and foreign material are removed. From the breaker, the coal is transported to large raw-coal silos in which the coal is stored prior to being delivered to the coal washing plant.

The coal washing plant employs a mechanical gravity separation process followed by mechanical dewatering using centrifuges, cyclones, or cross-flow screens. After being cleaned, the coal is conveyed to clean-coal silos. The refuse from the cleaning plant is thickened and centrifuged to remove water before being placed in the refuse bin with the larger refuse.

After being cleaned, the coal can be transported to market by whatever means are available.

Module Elements and Data

The underground coal mining module consists of two elements: (1) the coal mine and (2) the coal preparation plant. Table 6.5 describes each of these elements.

6.6.1b Surface Coal Mining

Discussion of Process

Surface coal mining can be divided into several mining methods, including area strip mining, open-pit strip mining, contour strip mining, and auger mining. As with underground mining methods, each of these surface mining methods is applicable under a specific set of topographic, geologic, and economic conditions.

Area strip mining is the major strip mining method used on Midwestern and some Western coal lands and has been selected to represent surface coal mining in this handbook. The total mining operation may be divided into four major areas of activity.

The first of these areas is the removal of overburden from atop the coal. Blasting with light charges is usually done in preparation for stripping to improve the "diggability" of the ground. Blasting is essential in solid formations and is often performed where not absolutely necessary, as it reduces costs by reducing the difficulty of digging. The overburden can be stripped by power shovel, dragline, or bucket wheel. Power shovels have been assumed for this handbook. Top soil that is obtained during the overburden removal process is reserved for reclamation, and the remaining overburden is placed in a spoil bank.

The second area of activity is the actual mining of the coal. As with the overburden, some light blasting is done to make the coal easier to dig. Power shovels are then used to load the coal into large trucks that haul the coal to the coal preparation facility.

The third area of activity is the crushing and cleaning of the coal in preparation for transport to market. Descriptions of two levels of effort for coal preparation are presented in the underground coal mining section and will not be repeated here. However, for the sake of clarity when performing

TABLE 6.5

Module: Underground Coal Mining

Element 1: Coal Mine

(a) Equipment, facilities

Continuous miners
Roof bolters
Feeder breakers
Rock dusters
Loaders
Trickle dusters
Face conveyors
Sherarers
Miscellaneous longwall equipment
Miscellaneous underground equipment
Shuttle cars
Transformers
Miscellaneous - buildings
Sump pumps

(b) Assumptions

(1) Energy and materials developed for underground mines with annual ROM production of 1,800,000 ton/yr and 3,600,000 ton/yr.
(2) Life of mine construction materials = life of mine
Life of mine equipment materials = 10 years

(c) Guidelines on data

(1) Data must be multiplied by tons per year of ROM coal.

(d) Data

(1) Direct energy per 1,800,000 tons of ROM coal:

Electricity	20,000,000 kwh	Ref. No. 3

Direct energy per 3,600,000 tons of ROM coal:

Electricity	40,000,000 kwh	Ref. No. 3

(2) Materials

Structural steel -	10,800 tons	Ref. No. 3
Concrete	1,100 tons	Ref. No. 3
Timber	715,000 lbs.	Ref. No. 3
Steel in equipment	3760 tons	Ref. No. 3
Rubber	413,000 lbs.	Ref. No. 3
Limestone	12 lbs/ton of coal	Ref. No. 3

TABLE 6.5

Continued

(3) Efficiency and Losses

- o Resource recovery rate is 55.5%. Coal that is unrecoverable is 44.5% of the resource.
- o Physical losses in transporting coal to the surface assumed to be negligible.
- o External energy to the module is totally consumed and is, therefore, lost.

(e) Data sources:

(1) Bureau of Land Management, 1981, Final Environmental Impact Statement--Moon Lake Power Project, Units 1 and 2: Salt Lake City, Utah, U.S. Department of the Interior, 578 p.
(2) Bureau of Land Management, 1981, Draft Environmental Impact Statement--Moon Lake Power Project, Units 1 and 2: Salt Lake City, Utah, U.S. Department of the Interior, 524 p.
(3) Private communications with mining and engineering companies.
(4) Schmidt, Richard A., 1979, Coal in America: McGraw-Hill, Inc., 458 p.
(5) Office of Technology Assessment, 1979, The direct use of coal: Congress of the United States, Washington, D.C., 411 p.

Element 2a: Coal Preparation Plant Without Washing

(a) Equipment, facilities

Hopper
Feeders
Conveyors
Crushers
Loadout facilities
Sampling facilities
Sump pumps

(b) Assumptions

(1) Energy consumption figures developed for ROM coal throughputs of 100,000 ton/yr, 1,000,000 ton/yr, 2,000,000 ton/yr, and 4,000,000 tpy.
(2) Energy embodied in materials has been excluded from this analysis.
(3) Coal loadout rate is 3,000 ton/hr.
(4) 240 operating days per year; 80% availability; single or double shift operation.

(c) Guidelines on data

(1) Data must be multiplied by tons per year of ROM coal feed to preparation plant.

TABLE 6.5

Continued

(d) Data

(1) Direct energy per 100,000 tons of ROM coal feed to preparation plant (single shift operation):

Electricity	3.85 kwh/ton	Ref. No. 1

(2) Direct energy per 1,000,000 tons of ROM coal feed to preparation plant (single shift operation):

Electricity	1.54 kwh/ton	Ref. No. 1

(3) Direct energy per 1,000,000 tons of ROM coal feed to preparation plant (double shift operation):

Electricity	2.62 kwh/ton	Ref. No. 1

(4) Direct energy per 2,000,000 tons of ROM coal feed to preparation plant (single shift operation):

Electricity	1.12 kwh/ton	Ref. No. 1

(5) Direct energy per 2,000,000 tons of ROM coal feed to preparation plant (double shift operation:)

Electricity	1.54 kwh/ton	Ref. No. 1

(6) Direct energy per 4,000,000 tons of ROM coal feed to preparation plant (double shift operation):

Electricity	1.12 kwh/ton	Ref. No. 1

(7) Efficiency and Losses

- o Losses in the coal preparation plant are 0.5% of ROM coal throughput.
- o Electricity consumed in the process is accounted as a loss.

(e) Data sources

(1) Symonds, Donovan F., 1979, Report prepared for Colorado School of Mines Research Institute.

TABLE 6.5

Continued

Element 2b: Coal Mine

(a) Equipment, facilities

Dump trucks
Tractors
Graders
Scrapers
Loaders
Conveyors
Feeders
Pumps
Screens

(b) Assumptions

(1) Energy and materials figures developed for 1,800,000 ton/yr and 3,600,000 ton/yr of ROM coal feed to the coal preparation plant.
(2) The ROM coal has a heating value of 8675 Btu/lb, the cleaned coal has a heating value of 10,520 Btu/lb, and the refuse has a heating value of 3150 Btu/lb.

(c) Guidelines on data

(1) Data must be multiplied by tons per year of ROM coal feed to the preparation plant.

(d) Data

(1) Direct energy per 1,800,000 tons of ROM coal feed to the preparation plant.

Electricity	106.7 x 10^6 kwh	Ref. No. 1
Diesel fuel	219,050 gallons	Ref. No. 1
Gasoline	18,800 gallons	Ref. No. 1
Materials		
Steel, structural	1700 tons	Ref. No. 1
Concrete	36,693 tons	Ref. No. 1
Rubber	35,000 lbs	Ref. No. 1
Steel, equipment	500 tons	Ref. No. 1

TABLE 6.5

Continued

(2) Direct energy per 3,600,000 tons of ROM coal feed to the preparation plant.

Electricity	109.7 x 10^6 kwh	Ref. No. 1
Diesel fuel	438,100 gallons	Ref. No. 1
Gasoline	37,600 gallons	Ref. No. 1
Materials		
Steel, structural	2720 tons	Ref. No. 1
Concrete	58,709 tons	Ref. No. 1
Rubber	28 tons	Ref. No. 1
Steel, equipment	800 tons	Ref. No. 1

(3) Efficiency and Losses

- o Physical losses in this coal preparation process are estimated to be 25% of the weight of the ROM coal.
- o Electricity and fuel used in the process are counted as losses from the module.

(e) Data sources

(1) Private communications with mining and engineering companies.

calculations, energy consumption figures for both levels of effort for coal preparation are presented with the energy consumption figures for both underground and surface coal mining.

The fourth area of activity associated with the surface mining of coal is reclamation of mined land. Reclamation is accomplished by smoothing the spoil bank, covering with top soil, and revegetating. Energy consumption associated with revegetating mined land has not been included in this handbook.

Module Elements and Data

The surface coal mining module consists of two elements: (1) coal mining and (2) coal preparation. Table 6.6 describes each of these elements. Overburden removal, mining reclamation, and support services are all included in the coal mining element.

TABLE 6.6

Module: Surface Coal Mining

Element 1: Coal Mining

(a) Equipment, facilities

Power shovels
Bulldozers
Dump trucks
Tank trucks
Drills
Graders
Loaders
Haulers
Scrapers
Pumps
Cranes
Miscellaneous light duty vehicles

(b) Assumptions

(1) 230 operating days per year with multiple shifts
(2) Energy and explosives consumption data that were developed for 18 surface mines have been smoothed to produce a linear relationship.
(3) Stripping ratios for the 18 surface mines ranged from 3.9 to 7.4 yd.^{3}/ton; average seam thickness ranged from 5 ft. to 34.5 ft.

(c) Guidelines on data

(1) Data must be multiplied by tons per year of ROM coal mined.

(d) Data

(1) Direct energy

Electricity	kwh/yr=(2.296 x tons/yr)-145,341 Minimum 148,050 kwh/yr	Ref. No. 1
Diesel fuel	gallons/yr=(0.806xtons/yr)+32,410 Minimum 78,750 gallons/yr	Ref. No. 1
Gasoline	0-470,000 tons/yr. of coal gallons/yr=(0.0885xtons/yr)-7088 Minimum 700 gallons/yr 470,000-2,380,000 tons/yr of coal 108,100 gallons/yr 2,380,000-2,900,000 tons/yr of coal 131,100 gallons/yr 2,900,000-4,500,000 tons/yr of coal 294,400 gallons/yr	Ref. No. 1

TABLE 6.6

Continued

(2) Materials

ANFO (explosives) tons/yr=(0.0010xtons coal/yr)-33 Ref. No. 1
Minimum 80 tons/yr

(3) Efficiency and Losses

- Physical loss of the in-place coal resource is estimated to be 15% of the resource.
- Electricity and fuel consumed in the mining operation is counted as a loss from the process.

(e) Data sources

(1) Internally generated by CSMRI based on limited information supplied by BLM for the net energy analysis of the Green River-Ham's Fork Coal Leasing Program.

Element 2a: Coal Preparation Plant Without Washing

(a) Equipment, facilities

Hopper
Feeders
Conveyors
Crushers
Loadout facilities
Sampling facilities
Sump pumps

(b) Assumptions

(1) Energy consumption figures developed for ROM coal throughputs of 100,000 ton/yr, 1,000,000 ton/yr, 2,000,000 ton/yr, and 4,000,000 tpy.
(2) Energy embodied in materials has been excluded from this analysis.
(3) Coal loadout rate is 3,000 ton/hr.
(4) 240 operating days per year; 80% availability; single or double shift operation.

(c) Guidelines on data

(1) Data must be multiplied by tons per year of ROM coal feed to preparation plant.

TABLE 6.6

Continued

(d) Data

(1) Direct energy per 100,000 tons of ROM coal feed to preparation plant (single shift operation):

Electricity 3.85 kwh/ton Ref. No. 1

(2) Direct energy per 1,000,000 tons of ROM coal feed to preparation plant (single shift operation):

Electricity 1.54 kwh/ton Ref. No. 1

(3) Direct energy per 1,000,000 tons of ROM coal feed to preparation plant (double shift operation):

Electricity 2.62 kwh/ton Ref. No. 1

(4) Direct energy per 2,000,000 tons of ROM coal feed to preparation plant (single shift operation):

Electricity 1.12 kwh/ton Ref. No. 1

(5) Direct energy per 2,000,000 tons of ROM coal feed to preparation plant (double shift operation):

Electricity 1.54 kwh/ton Ref. No. 1

(6) Direct energy per 4,000,000 tons of ROM coal feed to preparation plant (double shift operation):

Electricity 1.12 kwh/ton Ref. No. 1

(7) Efficiency and Losses

- Physical loss of coal in the preparation plant is estimated to be 0.5% of the ROM coal feed to the plant.
- Electricity consumed in the preparation plant is counted as a loss from the process.

(e) Data sources

(1) Symonds, Donovan F., 1979, Report prepared for Colorado School of Mines Research Institute.

TABLE 6.6

Continued

Element 2b: Coal Preparation with Washing

(a) Equipment, facilities

Dump trucks
Tractors
Graders
Scrapers
Loaders
Conveyors
Feeders
Pumps
Screens

(b) Assumptions

(1) Energy and materials figures developed for 1,800,000 ton/yr and 3,600,000 ton/yr of ROM coal feed to the coal preparation plant.

(2) The ROM coal has a heating value of 8675 Btu/lb, the cleaned coal has a heating value of 10,520 Btu/lb, and the refuse has a heating value of 3150 Btu/lb.

(c) Guidelines on data

(1) Data must be multiplied by tons per year of ROM coal feed to the preparation plant.

(d) Data

(1) Direct energy per 1,800,000 tons of ROM coal feed to the preparation plant.

Electricity	106.7 x 10^6 kwh	Ref. No. 1
Diesel fuel	219,050 gallons	Ref. No. 1
Gasoline	18,800 gallons	Ref. No. 1
Materials		
Steel, structural	1700 tons	Ref. No. 1
Concrete	36,693 tons	Ref. No. 1
Rubber	35,000 lbs	Ref. No. 1
Steel, equipment	500 tons	Ref. No. 1

TABLE 6.6

Continued

(2) Direct energy per 3,600,000 tons of ROM coal feed to the preparation plant.

Electricity	109.7 x 10^6 kwh	Ref. No. 1
Diesel fuel	438,100 gallons	Ref. No. 1
Gasoline	37,600 gallons	Ref. No. 1
Materials		
Steel, structural	2720 tons	Ref. No. 1
Concrete	58,709 tons	Ref. No. 1
Rubber	28 tons	Ref. No. 1
Steel, equipment	800 tons	Ref. No. 1

(3) Efficiency and Losses

- Physical losses in this coal preparation process are estimated to be 25% of the weight of the ROM coal.
- Electricity and fuel used in the process are counted as losses from the module.

(e) Data sources

(1) Private communications with mining and engineering companies.

6.6.2 Coal Transportation

Coal transportation by unit train and slurry pipeline are discussed here.

6.6.2a Unit Train

A coal unit train is a train which is dedicated exclusively to coal haulage. It consists of about 100 hopper cars and six 3,000 horsepower diesel locomotives. The speed is usually 20 to 50 miles per hour. Table 6.7 provides data on unit trains.

TABLE 6.7

Module: Coal Unit Train

(a) Equipment, facilities

Track, switches, signals
Hopper cars
Diesel locomotives
(Loading/unloading facilities assumed as part of other modules)

(b) Assumptions

(1) 100-car trains, typical Western hauls

(c) Guidelines on data

(1) Data are on a ton-mile basis

(d) Data

(1) Direct energy

Diesel fuel	390 Btu/ton-mile	Ref. No. 1
Steel	0.00004 tons/ton-mile	Ref. No. 1

(e) Data Sources

(1) Office of Technology Assessment, 1981, A technology assessment of coal slurry pipelines; Washington, D.C., Congress of the United States, 155 pages.

6.6.2b Coal Slurry Pipeline

Discussion of Process

Coal slurry pipelines are a method of transporting coal from a mine to a point of utilization, such as a power plant. In general, the coal is transported through the pipeline by water. However, other carrier fluids include liquid carbon dioxide, methanol, crude oil, and various fuel oils. Each of these liquid carriers have advantages that generally relate to the specific system under investigation. This discussion pertains only to coal slurry pipelines with water as the carrier fluid. The reason for this is twofold. First, the only operating long-distance coal slurry pipeline in the United States, the Black Mesa pipeline, utilizes water as the carrier fluid. Second, an adequate discussion of each of the other systems is beyond the scope of this handbook.

A coal slurry pipeline system is treated as a single module in this handbook. It consists of three elements: (1) the slurry preparation plant, (2) the slurry pipeline with a number of pumping stations, and (3) a slurry dewatering plant. A fourth element that would require energy and materials may be needed in many cases, namely a water supply system. This module is discussed in section 4.3.1 and should be included with the coal slurry pipeline system as necessary.

The first element, the slurry preparation plant, consists of a number of steps including size reduction of the coal, mixing of the solid and liquid phases, metering and adjusting the flows of both phases to assure constant throughput, and possibly the addition of reagents to improve the characteristics of the slurry in one way or another. Size reduction of the coal is the most important aspect of slurry preparation. The coal must be able to pass through the pumps and pipelines without blockage and must be of proper size to meet market specifications. The particle size of the Black Mesa pipeline coal is controlled such that the top size is approximately 3/16 in. and roughly 19% of the coal is finer that 44 micron. Primary crushing is performed with the dry coal and subsequent grinding is performed wet. After wet grinding, the slurry is transferred to a large agitated tank from which it is then fed to the pipeline fill tanks and diluted to the proper concentration.

The second element, the pipeline, is generally a buried steel pipe with pump stations located along the pipeline route. The number of pump stations that are required and the distance between stations are dependent upon the pressure drop in the pipeline. The factors important in determining the pipeline pressure drop are the terrain along the pipeline route, the particle size distribution, the solids concentration, the liquid viscosity, and the velocity at which the slurry travels within the pipeline. The velocity in the Black Mesa pipeline is between 5.0 and 5.7 feet per second along most of the route and is controlled such that the coal stays in suspension and does not result in excessive wear on the inside of the pipe.

The third element of a coal slurry pipeline system, the dewatering plant, can include a number of features. Dewatering is generally accomplished by sedimentation (material settling), pressure or vacuum filtration, or centrifuging. These techniques may be supplemented by thermal drying where the particular application requires coal with a very low moisture content.

Module Elements and Data

The coal slurry pipeline module consists of the three elements described above. Table 6.8 presents the assumptions and appropriate data for each of these elements.

TABLE 6.8

Module: Coal Slurry Pipeline

Element 1: Coal Slurry Preparation

(a) Equipment, Facilities

Material handling from transportation from mine
Breaker
Stockpile
Stockpile recovery
Load hopper
Conveyors
Surge bins
Feeders
Impact crushers
Water storage
Water pumps
Conveyors from crushers
Rod mills
Sump and slurry pump
Dust collector
Agitated Slurry tanks
Booster pumps
Calibration bin
Belt conveyors
Buildings: plant, maintenance, office, including cranes, heating, etc.
Transformers
Water holding ponds, tanks

(b) Assumptions

(1) Energy and materials data developed for 4,200,000 tons/year facility are assumed to apply to other sized facilities on a constant ton per year basis; i.e., no economies or diseconomies of sale are assumed.
(2) Slurry solids concentration is assumed to be approximately 50%, by weight.
(3) Coal from the mine is crushed to minus 2 inch prior to delivery to the slurry plant.
(4) No coal cleaning is involved.
(5) Coal losses at the slurry preparation plant are zero.
(6) Plant life assumed to be 35 years.

(c) Guidelines on data

(1) Energy data must be multiplied by tons per year of coal throughput.

(d) Data

(1) Direct energy for 4,2000,000 tons per year of coal delivered as coal slurry:

Electricity	34,130 kwh/ton	Ref. No. 2

TABLE 6.8

Continued

(2) Materials for 4,200,000 tons per year of coal delivered as coal slurry:

Structural steel	410 tons/yr	Ref. No. 3
Equipment steel	120 tons/yr	Ref. No. 3
Concrete	8810 tons/yr	Ref. No. 3
Rubber	5 tons/yr	Ref. No. 3

(3) Efficiency and Losses

- All direct energy and materials requirements are considered losses from the system.
- No material (coal) losses have been assumed from the system.

(e) Data Sources

(1) Montfort, J. G., 1980, Operating experience of the Black Mesa pipeline, in Proceedings of the 3rd International Coal Utilization Exhibition and Conference: Houston, Texas, p. 309-335.
(2) Banks, W. F., 1977, Energy consumption in the pipeline industry: DOE Report SAN-1171-2, December 31.
(3) Private communications with engineering companies.
(4) Banks, W. F. and Horton, J. H., 1977, Efficiency improvements in pipeline transportation systems: DOE Report SAN-1171-4.

Element 2: Slurry Pipeline and Pumping Stations

(a) Equipment, Facilities

- Steel line pipe
- Positive displacement or centrifugal slurry pumps
- Pressure relief equipment
- Pipeline control systems
- Microwave communications link between pump stations
- Shop facilities

(b) Assumptions

(1) Energy and materials data developed for 4,200,000 tons/year of dry coal throughput.
(2) Slurry solids concentration is assumed to be approximately 50% by weight.
(3) The pipeline is "telescoped" so that the pipe wall thickness at any given point is sufficient to withstand the hydraulic pressure at the point.
(4) Pipe diameter is nominal 16-inch.
(5) Pump stations are strategically located to maintain slurry flow.
(6) The terrain profile is relatively flat.

TABLE 6.8

Continued

(c) Guidelines on data

(1) The energy consumption data are presented as kwh per ton-mile and must be multiplied by the dry coal throughput (tons/year) and the pipeline distance (miles).
(2) The materials data are presented as tons per mile and must be multiplied by the pipeline distance (miles). These are one-time requirements. Replacement requirements are negligible.

(d) Data

(1) Direct energy for transporting 4,200,000 tons of coal per year in a slurry pipeline:

Electricity	0.0592 kwh/ton-mile	Ref. No. 1

(2) Materials for transporting 4,200,000 tons of coal per year in a slurry pipeline:

Steel pipe	219 tons/mile	Ref. No. 2
Concrete	130 tons/mile	Ref. No. 3

(3) Efficiency and Losses

- All direct energy and materials requirements are considered losses from the system.
- No material (coal) losses have been assumed.

(e) Data Sources

(1) Banks, W. F., 1977, Energy consumption in the pipeline industry: DOE Report SAN-1171-2, December 31.
(2) American Petroleum Institute, 1980, API specification for line pipe: Dallas, Texas, American Petroleum Institute, 62 p.
(3) Private communication with engineering company.

Element 3: Slurry Dewatering Plant

(a) Equipment, Facilities

Sedimentation bins
Filters
Centrifuges
Conveyors
Dryers
Pumps

TABLE 6.8

Continued

(b) Assumptions

(1) Energy and materials data developed for dewatering slurry from 50 wt % water to approximately 10 wt % water.
(2) Dry coal throughput is 4,200,000 tons per year.
(3) Extensive water cleanup is not required.

(c) Guidelines on data

(1) The energy consumption data are presented as Btu per ton of dry coal and must be multiplied by the dry coal throughput (tons per year).
(2) The materials data are presented as tons of material per year. These data are for a dry coal throughput of 4,200,000 tons per year and may be scaled to other throughputs by simple ratio. Data are annual requirements and include pro-rated figures for initial requirements as well as replacement requirements.

(d) Data

(1) Direct energy to dewater coal slurry (dry coal throughput = 4,200,000 tons/year):

Electricity	19 kwh/ton of coal	Ref. No. 1
Steam	710,000 Btu/ton of ocal	Ref. No. 1

(2) Materials to dewater coal slurry (dry coal throughput = 4,200,000 tons per year)

Structural steel	410 tons/yr	Ref. No. 2
Equipment steel	120 tons/yr	Ref. No. 2
Concrete	8810 tons/yr	Ref. No. 2
Rubber	5 tons/yr	Ref. No. 2

(3) Efficiency and losses

- All direct energy and materials requirements are considered losses from the system.
- Materials (coal) losses are estimated at 5% of the annual throughput, i.e.,

4,200,000 tons/yr x 5% = 210,000 tons/yr

(e) Data Sources

(1) Banks, W. F., 1977, Energy consumption in the pipeline industry: DOE Report SAN-1171-2, December 31.
(2) Private communication with engineering company.

TABLE 6.8

Continued

Module Energy Summary

(1) Principal Energy Input
Type: Coal, 2-inch x 0, dry
Quantity, units: 4,200,000 dry tons/year
Btu/unit: As applicable
Btu input: As applicable

(2) Principal Energy Loss

5% of Principal Energy Input

(3) Principal Energy Output

Type: Coal, w 10% moisture
Quantity: 3,990,000 dry tons/year

(4) Process Efficiency

95%

(5) Principal Energy to be used within Process Boundary

All of the Principal Energy Output is available for use, if desired.

6.7 COAL GASIFICATION

Introduction

Vast quantities of coal exist within the boundaries of the United States. However, because coal is a solid form of energy, many existing energy-consuming devices cannot now and will never be able to use coal directly. Additionally, when coal is burned, the impurities in the coal can produce ash residues and noxious gaseous emissions. Therefore, coal gasification technologies have been developed to convert coal from a solid into a gaseous form of energy that is more compatible with most end uses, is easier to transport and store, and is cleaner to use.

Coal gasification actually consists of many reactions that occur simultaneously to produce end products, intermediate compounds that react further, and by-products. However, the primary reaction consists of combining the carbon in coal with oxygen and steam to produce carbon monoxide and hydrogen. The by-products from coal gasification include carbon dioxide, sulfur compounds, tars, char, and many others. All gasification processes produce by-products, but the relative amounts of each are determined by the design and operating conditions of the gasifier. The gasification reactions are carried out at high temperatures, at a variety of pressures, in a very diverse set of gasifier vessel configurations.

After the coal is gasified, the impurities in the product gases must be removed before the gases can be used in an environmentally acceptable manner. A multitude of commercially proven processes can be used in a wide variety of different combinations to remove the particulates, oils and tars, sulfur compounds, and carbon dioxide. By-products from these processes can be used within the coal gasification facility (i.e., coal fines, tars, and oils recycled to the gasifier or used as fuel) or they can be sold (primarily elemental sulfur).

Gasifier Design

Many different gasification processes are currently under consideration, some of which have been demonstrated at a commercial scale while others have only been demonstrated in the laboratory or in pilot plants. The two basic categories of coal gasification technologies are: 1) in situ and 2) aboveground. For in situ processes, the coal is not mined, but is simply gasified underground in its natural position. Depending on the type of coal and the orientation and the thickness of the coal seam, several different in situ processes may be utilized. These various methods of in situ gasification are generally subdivided in four categories: 1) linked verticle well, 2) packed bed, 3) longwall generator, and 4) steeply dipping beds.

The aboveground processes may be similarly subdivided into four basic categories according to the design of the gasifier vessel. The aboveground processes are: 1) fixed-bed, 2) fluidized-bed, 3) entrained-bed, and 4) molten salt. The fixed-bed processes, the coal is fed to the top of the gasifier and, due to gravity, it moves slowly toward the bottom of the vessel where the ash is removed by a variety of mechanical devices. The air (or oxygen) and the steam are introduced into the bottom of the gasifier and pass countercurrent to the direction of flow of the coal. Lastly, the raw product gases pass out of

the top of the gasifier. In fluidized-bed processes, the coal if fed into the gasifier above the air (oxygen) injection point, somewhat similar to fixed-bed processes. However, the coal particles are much finer and are maintained in a balanced suspension by the upward flow of gases. Entrained-bed gasifiers are the only processes in which the air, steam, and coal are all introduced at the same end of the vessel. The very fine coal particles are rapidly swept through the gasifier cocurrently by the gases and react very quickly to form the desired products. Lastly, the molten-salt processes introduce the coal and air (or oxygen) into a bath of very hot molten material where the gasification reactions take place. Each type of process has its own odvantages and disadvantages and, depending on many factors (such as market for the gases, project schedule, type of coal etc.), each approach has its own merits.

In addition to the configuration of the gasification vessel, the various processes being developed differ by the methods used to feed the coal into the gasifier. One widely used method of feeding coal is the lock-hopper system in which the coal is passed in batches through an intermediate holding vessel that can be pressurized with each batch. Screw conveyors have also been demonstrated to be a feasible method for feeding coal. Another approach is to slurry the coal in a compatible fluid and pump the slurry into the gasifier. Additional studies are also being conducted on new coal-feeding methods.

Similarly, many methods have been developed for removing the ash from the gasifier. The ash can be removed in a granular form through a variety of grate mechanisms and lock-hopper systems. However, if the fusion temperature of the ash is exceeded in the gasifier, the ash becomes liquid and can be removed as a molten slag.

The more salient features of many coal gasification processes are summarized in Table 6.9. This listing is not meant to be all-inclusive of the large number of processes now being investigated. However, it may be useful to the user of this handbook who is not familiar with the names and acronyms of many of the processes.

Product Gas Heating Valve

Coal gasification processes can generate product gases with heating values of from 100 to 1000 Btu/scf. Therefore, these processes are often classified as producing low-Btu gases (100-300 Btu/scf), medium-Btu gases (300-600 Btu/scf), or high-Btu gases (1000 Btu/scf). This method of classification, however, is misleading in that it is not indicative of the actual gasification process per se. Rather, it is indicative of the auxillary process that may be used in conjunction with gasification. Although the terminology of low-, medium-, and high-Btu gasification is technically misleading, it provides a convenient basis for net-energy analysis. Therefore, this handbook will segregate the aboveground gasification processes into three categories (modules) according to the heating value of the product gases. The in situ processes will be presented as a fourth module.

The distinction between low- and medium-Btu gasification results from the exclusion or inclusion of one processing step, an air separation plant, into the gasification module. The oxygen required for the coal gasification reactions may be supplied from air injected into the gasifier or it may be supplied as pure oxygen that comes from an air separation plant. Low-Btu gases

TABLE 6.9

Description of Various Coal Gasification Processes

PROCESS NAME (Primary Developer)	STAGE OF DEVELOPMENT	OXYGEN SUPPLY	COAL FEED	ASH REMOVAL METHOD	TEMPERATURE AND PRESSURE	COMMENTS
FIXED-BED GASIFIERS:						
1) Lurgi Dry Ash (Lurgi Gesellschaft for Warme-und Chemotechnik Mbttm W. Germany)	commercial	normally oxygen but air can be used	1/4" to 2" via lock hoppers	revolving grate with lock hoppers	1100-1400°F 350-450 psig	In use for over 40 years. Primarily used to produce high-Btu gases. Generally not used for caking coals or those with low ash fusion temperatures. Relatively large amounts of methane, tars, oils, and phenols are produced.
2) Slagging Lurgi (British Gas Corp.; Conoco Coal Development Company)	pilot plant	oxygen	1/2" to 1" via lock hoppers	molten slag into a water quench then into lock hopper	1500-2000°F 300 psig	Developed from the Lurgi Dry Ash technology. Capable of processing caking coals. Produces high-Btu gases.
3) Stoic (Stoic Combustion Ltd., S. Africa; Foster Wheeler Corp.)	commercial	air		revolving grate into a water spal	1800°F atmospheric	A two-stage gasifier. Produces low-Btu gases.
4) Wellman-Galusha (McDowell-Wellman Co.; Wellman-Galusha Co.)	commercial	air or oxygen	1/4" to 2" via lock hoppers	revolving grate	2000-2400°F atmospheric	In use for over 30 years. May be used to produce low- or medium-Btu gases.
5) Woodall-Duckham (Gas Integrale, Italy; Woodall-Duckham Ltd.; England)	commercial	air or oxygen	1/4" to 2" via lock hoppers	revolving grate	1700-2200°F atmospheric	In use for over 30 years. A two-stage gasifier. May be used to produce low- or medium-Btu gases.

TABLE 6.9

Continuation

PROCESS NAME (Primary Developer)	STAGE OF DEVELOPMENT	OXYGEN SUPPLY	COAL FEED	ASH REMOVAL METHOD	TEMPERATURE AND PRESSURE	COMMENTS
FLUIDIZED-BED GASIFIERS:						
1) CO_2 Acceptor (Consolidation Coal Co.)	pilot plant	none	mins 8 mesh (-1/8") via lock hoppers	water quench tower	gassifiers : 1480-1550°F regenerators: 1850°F both at 150 psig	Produces medium-Btu gases. Heat is supplied by an "acceptor," usually limestone or dolomite, that reacts exothermically with CO_2 (carbon dioxide). The acceptor is regenerated by heat from combustion of char from the gasifier. Product gases are low in CO_2 and sulfur.
2) COGAS (COGAS Development Co.; FMC Corp.)	pilot plant	air or oxygen		molten slag	600-1600°F in several stages 25 psig	Used to gasify char from the COED coal liquefication process. Multiple stages, usually 4 to 6, are used. May be used to produce low- or medium-Btu gases.
3) HYGAS (Institute of Gas Technology)	pilot plant	none; the gasifier uses hydrogen	minus 14 mesh (-1/16") slurried in oil, then pumped into the gasifier	non-slagging slurry	1200-1800°F 1000-1500 psig	Gasifier uses hydrogen directly, thus producing gases with relatively high heating values. Caking coals must be pretreated. Designed to be integrated with methanation.
4) Synthane (U.S. Bureau of Mines)	pilot plant	oxygen	minus 20 mesh (-1/32") via lock hoppers	lock hoppers	1300-1800°F 600-1000 psig	Produces medium-Btu gases with high methane concentrations. Caking coals must be pretreated. Designed to be integrated with methanation.

TABLE 6.9

Continuation

PROCESS NAME (Primary Developer)	STAGE OF DEVELOPMENT	OXYGEN SUPPLY	COAL FEED	ASH REMOVAL METHOD	TEMPERATURE AND PRESSURE	COMMENTS
FLUIDIZED-BED GASIFIERS:						
5) U-Gas (Institute of Gas Technology	pilot plant	air or oxygen	minus 1/4"	sloped grid into lock hoppers	1800-2000°F 50-350 psig	Caking coals must be pretreated. Ash if agglomerated into large particles and selectivity removed. May be used to produce low- or medium-Btu gases.
6) Westinghouse (Westinghouse)	process development unit	air	minus 6 mesh (-1/8")		1st Stage= 1600°F 2nd Stage= 2000°F both at 175 psig	Two-stage process designed primarily for use with a combined-cycle electric power generating plant. Desulfurization is accomplished with a sorbent such as dolomite. Produces low-Btu gases.
7) Winkler (Davy Powergas, Inc.)	commercial	normally air, but oxygen can be used	Minus 8 mesh via variable speed screw conveyor	variable speed screw conveyor	1500-2000°F atmospheric	In use for over 40 years. Primarily used to produce low-Btu gases. A high-pressure process is being developed.

TABLE 6.9

Continuation

PROCESS NAME (Primary Developer)	STAGE OF DEVELOPMENT	OXYGEN SUPPLY	COAL FEED	ASH REMOVAL METHOD	TEMPERATURE AND PRESSURE	COMMENTS
ENTRAINED-BED GASIFIERS:						
1) BI-GAS (Bituminous Coal Research, Inc.)	pilot plant	oxygen	pulverized(a) coal slurried in water	molten slag	1st Stage: 1800°F 2nd Stage: 2700-3000°F Both at 1500 psig	Two-stage process designed to produce medium-Btu gases for subsequent methanation. Obtains high methane yields with no oils or tars.
2) Combustion Engineering (Combustion Engineering, Inc.)	pilot plant	normally air, but oxygen can be used	pulverized(a) coal	molten slag	1st Stage= 1600°F 2nd Stage= 3200°F Both at atm. pressure	Two-stage process primarily designed to produce low-Btu gases. Medium-Btu gases can be produced if oxygen blown.
3) Koppers-Totzek (Krupp-Koppers GmbH, W. Germany; KBW Gasification Systems, Inc.)	commercial	oxygen	pulverized(a) coal injected with steam and oxygen	molten slag	2700-3300°F 0-10 psig	In use for over 30 years. One-stage process designed to produce medium-Btu gases for methane or ammonia synthesis.
4) Shell-Koppers (Shell Internationale Petroleum Maatschappij B.V., The Netherlands; Krupp-Koppers GmbH, W. Germany	pilot plant	oxygen	pulverized(a) coal via lock koppers	molten slag	2700°F 300-500 psig	Developed from the Koppers-Totzek process. No oils or tars are produced.

(a) Pulverized coal is defined as 70% or more smaller than 200 mesh (-0.003")

TABLE 6.9

Continuation

PROCESS NAME (Primary Developer)	STAGE OF DEVELOPMENT	OXYGEN SUPPLY	COAL FEED	ASH REMOVAL METHOD	TEMPERATURE AND PRESSURE	COMMENTS
ENTRAINED-BED GASIFIERS:						
5) Texaco (Texaco Development Co.)	pilot plant	air or oxygen	pulverized(a) coal slurried in water or oil	molten slag	2500°F 300-1200 psig	One-stage process capable of using many types of coal to produce low- or medium-Btu gases. No oils or tars are produced.
MOLTEN-SALT GASIFIERS:						
1) Rockgas (Rockwell International Corp.)	pilot plant	air	less than 1/4" coal mixed with sodium carbonate and transported by air	withdrawn with molten salt, quenched, and filtered	1800°F 300-450 psig	Molten sodium carbonate retains the sulfur and ash in the melt. Designed to produce low-Btu fuel gases for electric power generation.

result from an air-blown process because the nitrogen that enters the gasifier with the air dilutes that product gases. However, an oxygen-blown process generates medium-Btu gases that are not diluted with nitrogen.

The distinction between medium- and high-Btu processes also results from incorporating additional processing steps into the module. A two-step process may be used to upgrade medium-Btu gases to a high-Btu gas methane. The two-step process consists of first adjusting the ratio of carbon monoxide and hydrogen in the medium-Btu product gas to a value of 1:3 by a reaction referred to as shift conversion. After the proper ratio is achieved, the gases can be converted to methane by a variety of methanation processes. Because it is so dilute, low-Btu gases cannot be economically converted to high-Btu products.

It should be noted that low-Btu gasification processes are generally relatively simple and, thus, require less capital investment in equipment and entail less process energy losses. However, the product gases are of relatively low value (the quality of energy, as discussed earlier) and can be used for only a limited number of applications. On the other hand, high-Btu gases have a higher value, but require more complex processing with increased energy consumption. Medium-Btu gasification processes are somewhere in the middle with regard to both complexity (and, thus, energy used in processing) and value of the product. The distinction between low-, medium-, and high-Btu gas production from coal is presented schematically in Figure 6.1.

6.7.1 Low-Btu Aboveground Coal Gasification

Discussion of Process

Low-Btu coal gasification processes are used to produce clean-burning gaseous fuels for large industrial boilers and for electric power generating plants. Because the products gases have low heating values (100-300 Btu/scf), they can only be economically transported in pipelines for short distances. Hence, the user of the gases must be physically located very close to the gasification process.

The low-Btu aboveground coal gasification process is treated as a single module with one element in this handbook. It consists of four distinct operations: 1) coal preparation, 2) coal gasification, 3) product gas cleanup, and 4) solid and aqueous waste treatment and disposal.

The coal preparation operation can be highly variable, depending on the type of gasifier and the type of coal. All coal gasification processes require some degree of coal preparation which may simply be crushing and grinding the coal to the proper size. Additionally, some processes require the coal to be mildly heated to remove tars and water that cause the coal particles to stick together in the gasifier (referred to as caking). Although the coal may require other preparation processes such as benefication, cleaning, and drying, they are not included in the module for this handbook.

The gasification process consists of reacting the carbon in coal with oxygen and steam to form carbon monoxide and hydrogen. Many other impurities and by-products are also produced within the gasifier. Gas cleanup is required so that the product gases from the gasifier may be used in an environmentally

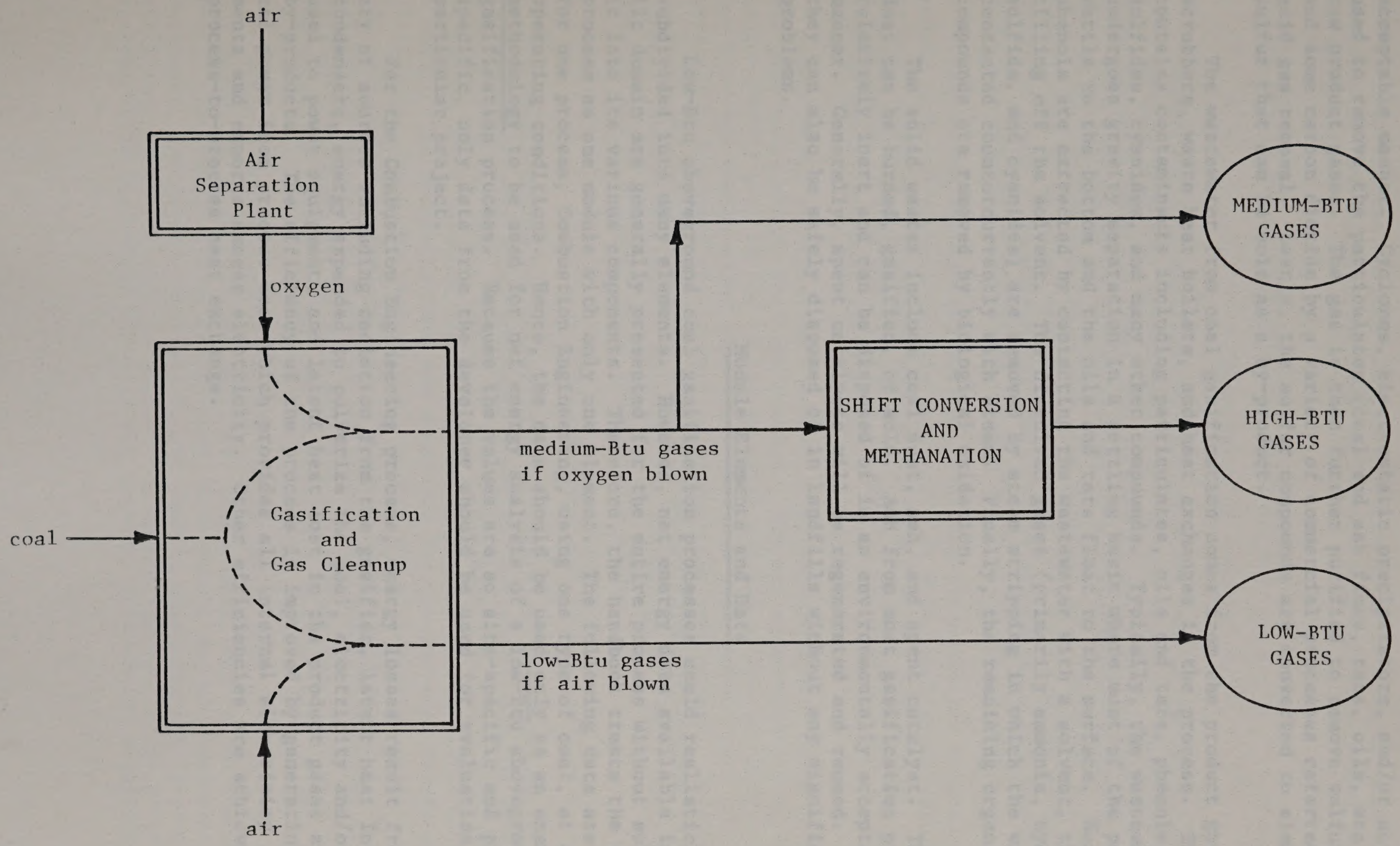

air
Air Separation Plant
oxygen
coal
Gasification and Gas Cleanup
air
medium-Btu gases if oxygen blown
low-Btu gases if air blown
SHIFT CONVERSION AND METHANATION
MEDIUM-BTU GASES
HIGH-BTU GASES
LOW-BTU GASES

FIGURE 6.1

Production of Low-, Medium-, and High-Btu Gases from Coal

acceptable manner. Cyclones, electrostatic precipitators, and/or scrubbers are used to remove the particulates (coal and ash fines, tars, oils, etc.) from the raw product gases. The gas is then further purified to remove sulfur compounds and some carbon dioxide by a variety of commercial processes referred to as acid gas removal. Lastly, the sulfur compounds are converted to elemental sulfur that can be sold as a by-product.

The wastewater from coal gasification comes from the product gas scrubbers, waste heat boilers, and heat exchanges in the process. This water contains contaminants including particulates, oils and tars, phenols, ammonia, sulfides, cyanides, and many other compounds. Typically, the wastewater first undergoes gravity separation in a settling basin where most of the particulates settle to the bottom and the oils and tars float to the surface. Next, the phenols are extracted by contacting the wastewater with a solvent, then distilling off the solvent. The dissolved gases (primarily ammonia, hydrogen, sulfide, and cyanides) are removed by steam stripping in which the water is contacted countercurrently with steam. Finally, the remaining organic compounds are removed by biological oxidation.

The solid wastes include coal dust, ash, and spent catalyst. The coal dust can be burned, gasified, or sold. Ash from most gasification processes is relatively inert and can be disposed of in an environmentally acceptable manner. Generally, spent catalysts will be regenerated and reused. If not, they can also be safely disposed of in landfills without any significant problems.

Module Elements and Data

Low-Btu aboveground coal gasification processes could realistically be subdivided into many elements. However, net energy data available in the public domain are generally presented for the entire process without subdividing it into its various components. Therefore, the handbook treats the entire process as one module with only one element. The following data are presented for one process, Combustion Engineering, using one type of coal, at one set of operating conditions. Hence, the data should be used only as an example of the methodology to be used for net energy analysis of a low-Btu aboveground coal gasification process. Because the values are so site-specific and process-specific, only data from the developer should be used for evaluation of a particular project.

For the Combustion Engineering process, energy losses result from a variety of sources including radiation from the gasifier, latent heat lost in the condensers, energy expended to pulverize the coal, electricity and/or steam used to power equipment, and latent heat lost in the product gases and the by-products. The efficiency of the process is improved by generating electrical power from process heat which provides all internal electricity requirements and exports excess electricity. Other efficiencies are achieved by process-to-process heat exchange.

A flow diagram for the Combustion Engineering process is presented in Figure 6.2. The assumptions and appropriate data for this module are presented in Table 6.10.

6.7.2 Medium-Btu Aboveground Coal Gasification

Discussion of Process

Medium-Btu coal gasification processes are used to generate clean gases with heating values of approximately 300 to 600 Btu/scf. These gases, often referred to a synthesis gases, can be used as fuels for large-scale consumers much like low-Btu gases or can be used as a feedstock for a variety of processes. Medium-Btu gases have been proposed as a feedstock for the manufacture of ammonia, methanol, and other chemicals and for methanation to high-Btu gases. The medium-Btu gases can be economically transported in specially designated pipelines for distances of up to 200 miles.

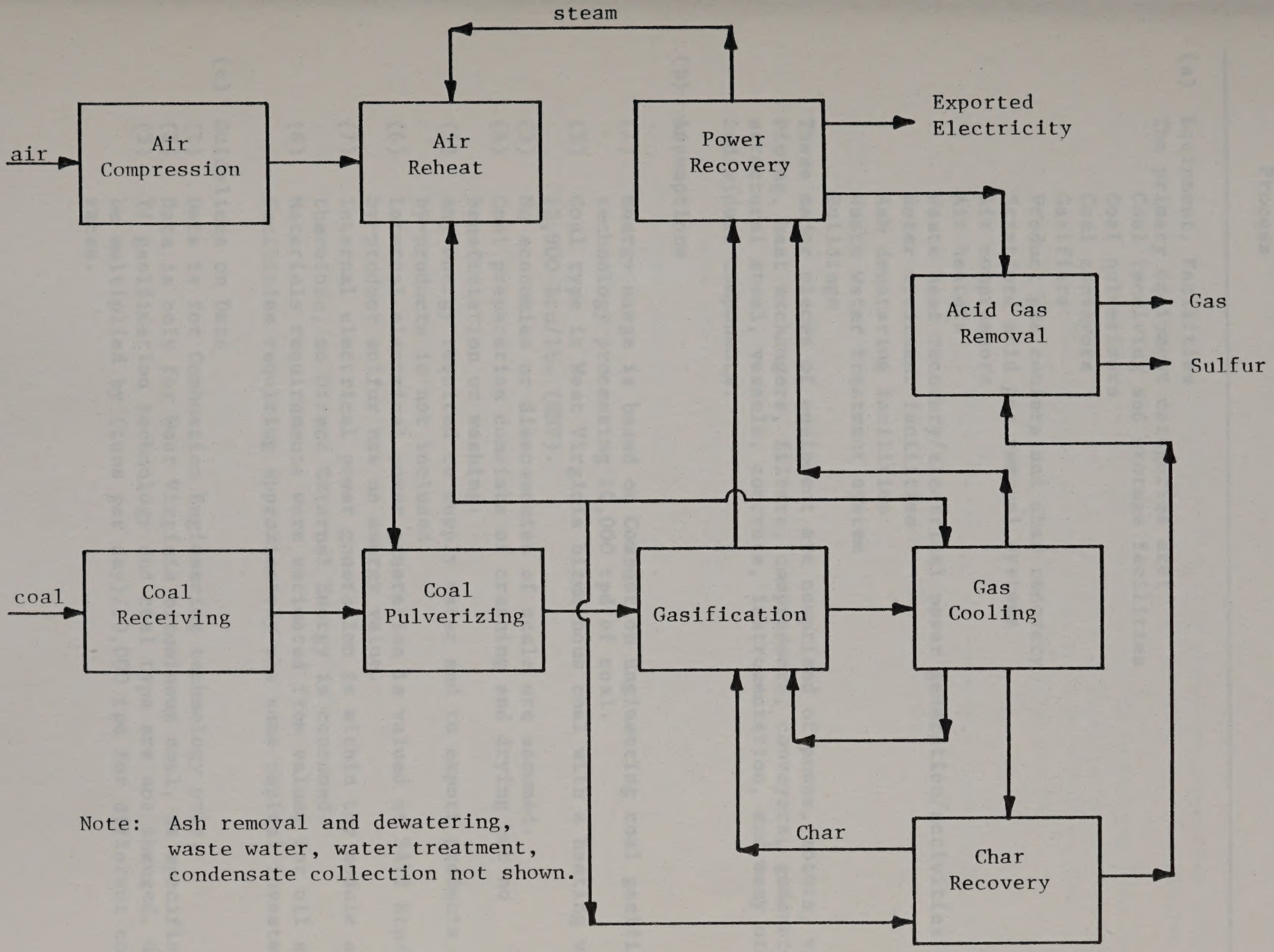
Medium-Btu aboveground coal gasification processes are treated as a single module with one element in this handbook. As with low-Btu aboveground gasification, medium-Btu processes consist of four distinct operations: 1) coal preparation, 2) coal gasification, 3) product gas cleanup, and 4) solid and aqueous waste treatment and disposal.

Medium-Btu gasification, however, also incorporates a fifth operation, an air separation plant, into the process. The air separation plant produces pure oxygen (+95%) that is fed to the gasifier instead of the air that is used for low-Btu coal gasification processes. Several well-demonstrated commercial air separation processes can be used to produce the pure oxygen. Medium-Btu gasification processes require more capital expenditures and consume more energy than do low-Btu processes. However, the product gases from a medium-Btu process are of a higher value than low-Btu gases.

Module Elements and Data

Although medium-Btu aboveground coal gasification processes could be realistically subdivided into many elements, net energy data is generally not available in the public domain in sufficient detail to allow such an analysis. Therefore, this handbook treats the entire process as one module with only one element. The following data are presented for one process, Texaco gasification technology, using one type of coal, at one set of operating conditions. Hence, the data should be used only as an example of the methodology to be used for net energy analysis of a medium-Btu aboveground coal gasification process. Because the values are so site specific and process specific, only data from the developer should be used for evaluation of a particular project.

For the Texaco process, energy losses result from a variety of sources including radiation from the gasifier, latent heat lost in the condenses, energy expended to pulverize the coal, electricity and/or steam used to power equipment, and latent heat lost in the product gases and the by-products. The efficiency of the process is improved by generating electrical power from process waste heat which provides all internal electricity requirements and



Note: Ash removal and dewatering, waste water, water treatment, condensate collection not shown.

FIGURE 6.2

Low-Btu Gas: Combustion Engineering Process Schematic

TABLE 6.10

Module: Low-Btu Aboveground Coal Gasification Using the Combustion Engineering Process

---

(a) Equipment, Facilities

The primary equipment categories are:

Coal receiving and storage facilities
Coal pulverizers
Coal conveyors
Gasifiers
Product gas coolers and char recovery
Stretford acid gas removal systems
Air compressors
Air heaters
Waste heat recovery/electrical power generation/activities
Water treatment facilities
Ash dewatering facilities
Waste water treatment system
Buildings

These major pieces of equipment are comprised of pumps, motors, valves, piping, heat exchangers, filters, compressors, conveyors, generators, structural steel, vessels, concrete, instrumentation, and many other individual components.

(b) Assumptions

(1) Energy usage is based on Combustion Engineering coal gasification technology processing 10,000 tpd of coal.
(2) Coal type is West Virginia bituminous coal with a heating value of 12,900 Btu/lb. (HHV).
(3) No economies or diseconomies of scale are assumed.
(4) Coal preparation consists of crushing and drying but no beneficiation or washing.
(5) Any energy required to supply water and to export products and by-products is not included.
(6) Internal electrical power generation is valued at 3413 Btu/Kwh; by-product sulfur has no energy value.
(7) Internal electrical power generation is within the module and, therefore, so Direct External Energy is consumed.
(8) Materials requirements were estimated from values for oil shale facilities requiring approximately the same capital investment.

(c) Guidelines on Data

(1) Data is for Combustion Engineering technology only.
(2) Data is only for West Virginia bituminous coal, as specified above.
(3) If gasification technology and coal type are not changed, data may be multiplied by (tons per day)/10,000 tpd for different coal feed rates.

TABLE 6.10

Continued

(d) Data
- (1) Direct Energy: Because electrical power and steam are generated within the module, no Direct Energy is used by the process.
- (2) Materials: No known.
- (3) Losses: Principle energy losses occur as radiation from the gasifier, latent heat lost in condensers, energy expended to pulverize the coal, electricity and/or steam used to power equipment, and the latent heat of the product gases and by-products.

(e) Data Sources
- (1) Winsor, Lloyd, 1980, Technical and economic comparison of replacing oil with low- or medium-Btu gas in a utility power plant boiler, in Coal technology '80: Houston, TX, p. 33-59.

Module Energy Summary

(1) Principal Energy Input

Type: West Virginia bituminous coal
Quantity, units: 10,000 tons/day
Btu/unit: 12,900 Btu/lb
Btu input: 10750 x 10^6 Btu/hour

(2) Principal Energy Loss

2883 x 10^6 Btu/hour

(3) Principal Energy Output

Type:	104 Btu/scf gas	Electricity
Quantity:	7214 x 10^6 Btu/hour	653 x 10^6 Btu/hour

(4) Process Efficiency

73.2 %

(5) Principal Energy to be used within Process Boundary

Assumed to be none, but electricity is available.

TABLE 6.11

Module: Medium-Btu Aboveground Coal Gasification Using the Texaco Process

---

(a) Equipment, Facilities

The primary equipment categories are:

- Coal receiving and storage facilities
- Coal pulverizers
- Coal conveyors
- Gasifiers
- Air separation facilities
- Product gas coolers and char recovery
- Acid gas removal systems
- Waste heat recovery/electrical power generation/activities
- Water treatment facilities
- Ash dewatering facilities
- Waste water treatment system
- Buildings

These major pieces of equipment are comprised of pumps, motors, valves, piping, heat exchangers, filters, compressors, conveyors, generators, structural steel, vessels, concrete, instrumentation, and many other individual components.

(b) Assumptions

(1) Energy usage is based on Texaco coal gasification technology processing 10,000 tpd of coal.

(2) Coal type is West Virginia bituminous coal with a heating value of 12,900 Btu/lb. (HHV).

(3) No economies or diseconomies of scale are assumed.

(4) Coal preparation consists of crushing and drying but no beneficiation or washing.

(5) Any energy required to supply water and to export products and by-products is not included.

(6) Internal electrical power generation is valued at 3413 Btu/Kwh; by-product sulfur has no energy value.

(7) Internal electrical power generation is within the module and, therefore, so Direct External Energy is consumed.

(8) Materials requirements were estimated from values for oil shale facilities requiring approximately the same capital investment.

(c) Guidelines on Data

(1) Data is for Texaco technology only.

(2) Data is only for West Virginia bituminous coal, as specified above.

(3) If gasification technology and coal type are not changed, data may be multiplied by (tons per day)/10,000 tpd for different coal feed rates.

TABLE 6.11

Continued

(d) Data

(1) Direct Energy: Because electrical power and steam are generated within the module, no Direct Energy is used by the process.

(2) Materials: Not known.

(3) Losses: Principle energy losses occur as radiation from the gasifier, latent heat lost in condensers, energy expended to pulverize the coal, electricity and/or steam used to power equipment, and the latent heat of the product gases and by-products.

(e) Data Sources

(1) Winsor, Lloyd, 1980, Technical and economic comparison of replacing oil with low- or medium-Btu gas in a utility power plant boiler, in Coal technology '80: Houston, TX, p. 33-59.

Module Energy Summary

(1) Principal Energy Input

Type: West Virginia bituminous coal
Quantity, units: 10,000 tons/day
Btu/unit: 12900 Btu/lb
Btu input: 10750 Btu/hour

(2) Principal Energy Loss

3342×10^6 Btu/hour

(3) Principal Energy Output

Type:	292 Btu/scf gas	Electricity
Quantity:	7110×10^6 Btu/hour	298×10^6 Btu/hour

(4) Process Efficiency

68.9 %

(5) Principal Energy to be used within Process Boundary

Assumed to be none, but electricity is available.

exports excess electricity. Other efficiencies are achieved by process-to-process heat exchange.

A flow diagram for the Texaco process is presented in Figure 6.3. The assumptions and appropriate data for this module are presented in Table 6.11.

6.7.3 High-Btu Aboveground Coal Gasification

Discussion of Process

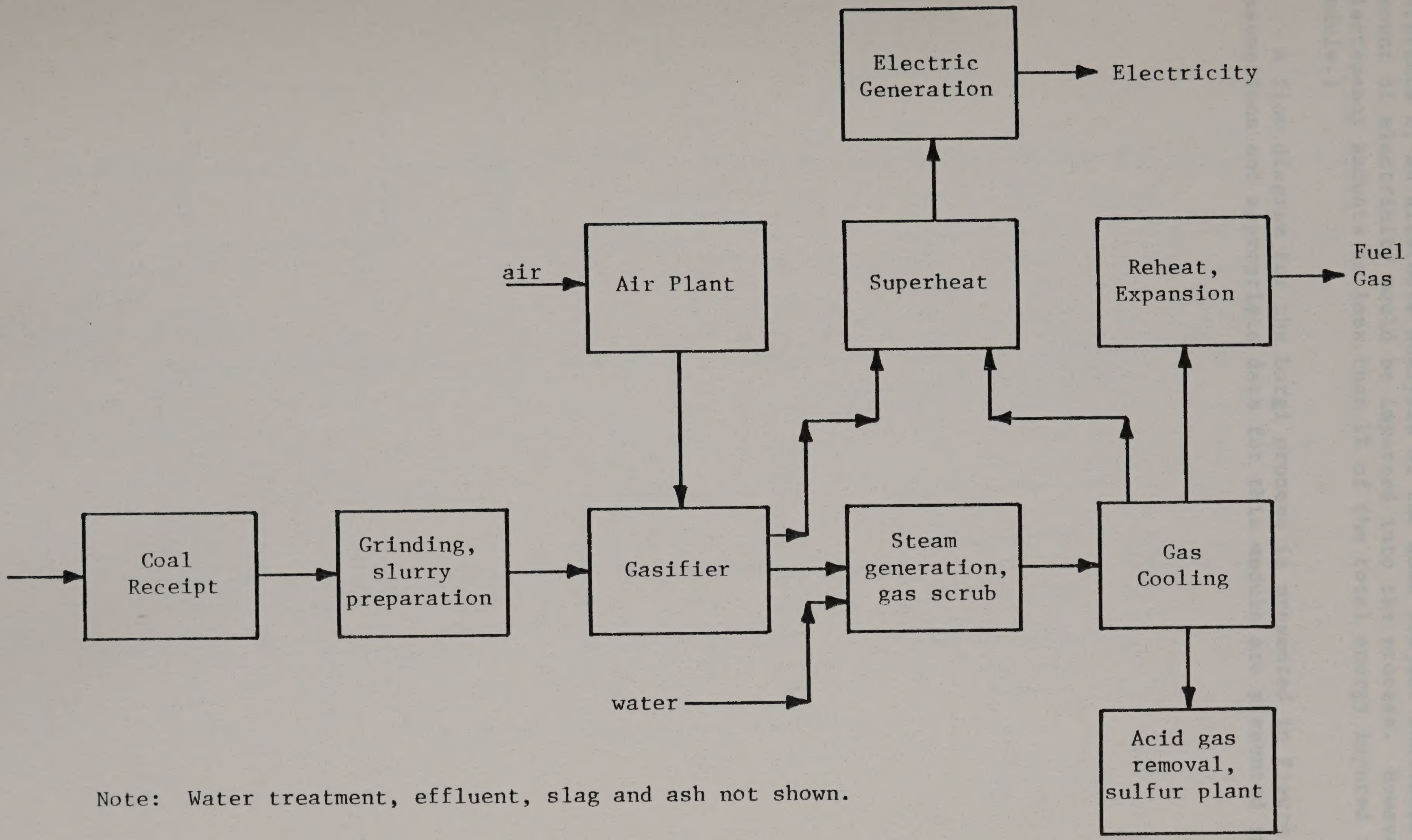
High-Btu coal gasification processes are used to generate methane, the primary constituent in natural gas, from coal. The methane can be used as a fuel by all sectors of society including industrical, commercial, and residential consumers. Conceivably the methane from coal could also be used as a feedstock for a variety of processes, but medium-Btu gases from coal are more likely to be used as feedstocks. The methane from a high-Btu gasification process can be introduced into the existing natural gas pipeline network and transported over long distances.

High-Btu aboveground coal gasification processes are treated as a single module with one element in this handbook. These processes involve coal preparation, coal gasification, product gas cleanup, solid and aqueous waste treatment, and oxygen production as described for medium-Btu coal gasification. However, the product gases (synthesis gases) are further treated to product high-Btu methane from the medium-Btu gases. The additional processing steps involve adjusting the carbon monoxide/hydrogen ratio to the desired value of 1:3 by a reaction referred to as shift conversion. These gases are then purified to remove sulfur compounds and the carbon dioxide formed during gasification and shift conversion. Finally, the gases can be converted to methane in a variety of commercially available processes. High-Btu gasification processes generate a commodity, methane, with a high value to society. However, a significantly more complex process is required to upgrade the medium-Btu gases from the gasifier. (Low-Btu gases cannot be economically converted to methane because of their dilute nature.)

Module Elements and Data

The high-Btu coal gasification processes could be subdivided into many elements. However, nte energy data available in the public domain is generally not available in sufficient detail to allos such an analysis. Therefore, this handbook treats the entire process as one module with only one element. The following data are presented for one process, Lurgi gasification technology, using one type of coal, at one set of operating conditions. Hence, the data should be used only as an example of the methodology to be used for net energy analysis of a high-Btu aboveground coal gasification process. Because the values are so site specific and process specific, only data from the developer should be used for evaluation of a particular project.

For the Lurgi process, energy losses result from a variety of sources including radiation from the gasifier latent heat lost in the condensers, energy expended to crush the coal, electricity and/or steam used to power equipment, unreacted coal in the ash, and latent heat lost in the products and by-products. The efficiency of the process specified in Table 6.12 is improved by generating electrical power from coal fires and process heat which provides



Note: Water treatment, effluent, slag and ash not shown.

FIGURE 6.3

Medium-Btu Gas: Texaco Process Schematic

all internal electricity requirements and exports excess electricity. (In Reference 2, an alternate analysis of the same project indicated a slight amount of electricity would be imported into the process. However, this discrepancy amounts to less than 1% of the total energy inputed into the module.)

A flow diagram for the Lurgi process is presented in Figure 6.4. The assumptions and appropriate data for this module are presented in Table 6.12.

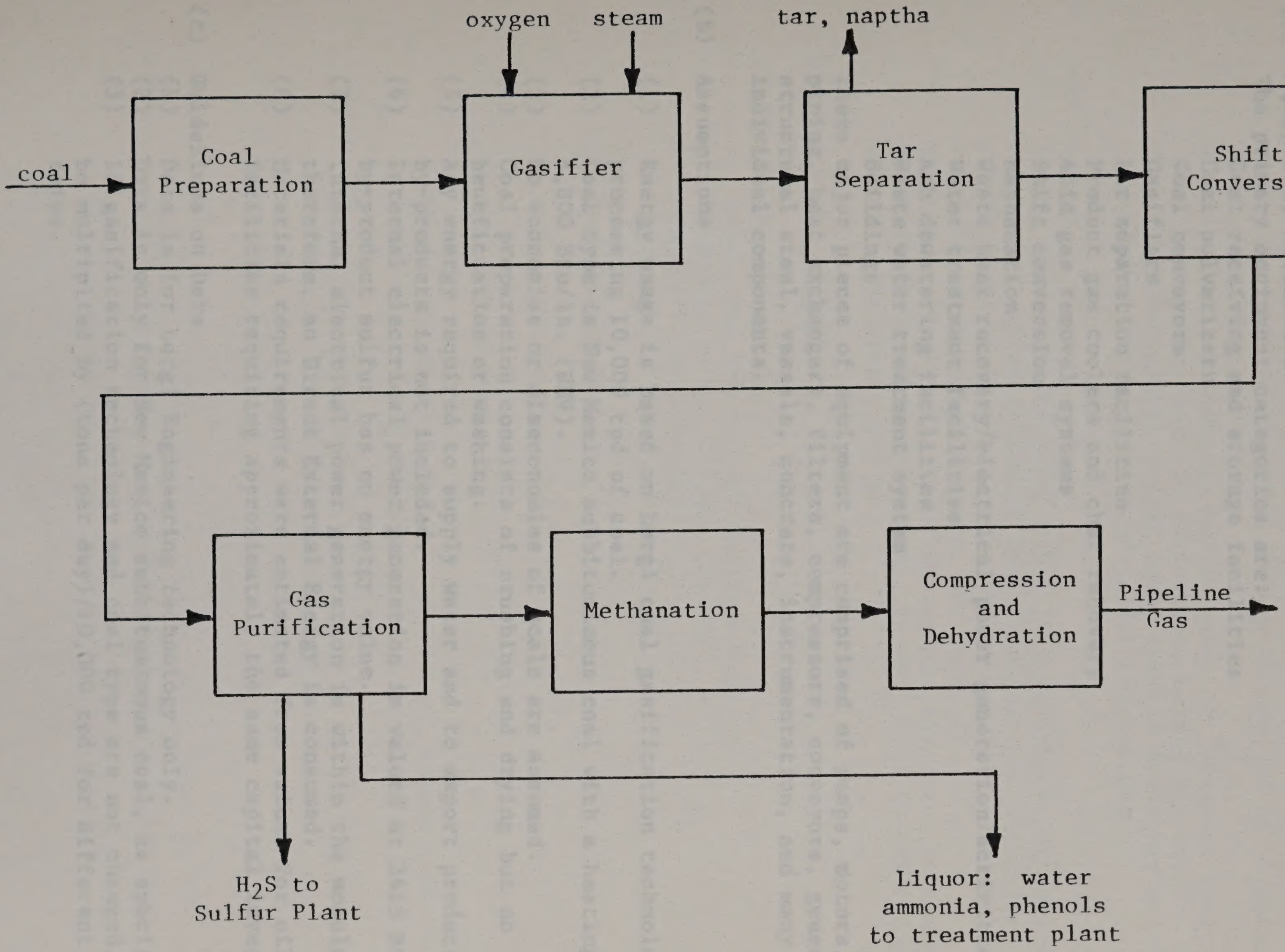


FIGURE 6.4

High-Btu Gas: Lurgi Process Schematic

TABLE 6.12

Module: High-Btu Aboveground Coal Gasification Using the Texaco Engineering Process

(a) Equipment, Facilities

The primary equipment categories are:

- Coal receiving and storage facilities
- Coal pulverizers
- Coal conveyors
- Gasifiers
- Air separation facilities
- Product gas coolers and char recovery
- Acid gas removal systems
- Shift conversion
- Methanation
- Waste heat recovery/electrical power generation/activities
- Water treatment facilities
- Ash dewatering facilities
- Waste water treatment system
- Buildings

These major pieces of equipment are comprised of pumps, motors, valves, piping, heat exchangers, filters, compressors, conveyors, generators, structural steel, vessels, concrete, instrumentation, and many other individual components.

(b) Assumptions

(1) Energy usage is based on Lurgi coal gasification technology processing 10,000 tpd of coal.

(2) Coal type is New Mexico subbituminous coal with a heating value of 8,800 Btu/lb. (HHV).

(3) No economies or diseconomies of scale are assumed.

(4) Coal preparation consists of crushing and drying but no beneficiation or washing.

(5) Any energy required to supply water and to export products and by-products is not included.

(6) Internal electrical power generation is valued at 3413 Btu/Kwh; by-product sulfur has no energy value.

(7) Internal electrical power generation is within the module and, therefore, so Direct External Energy is consumed.

(8) Materials requirements were estimated from values for oil shale facilities requiring approximately the same capital investment.

(c) Guidelines on Data

(1) Data is for Lurgi Engineering technology only.

(2) Data is only for New Mexico subbituminous coal, as specified above.

(3) If gasification technology and coal type are not changed, data may be multiplied by (tons per day)/10,000 tpd for different coal feed rates.

TABLE 6.12

Continued

(d) Data

- (1) Direct Energy: Because electrical power and steam are generated within the module, no Direct Energy is used by the process.
- (2) Materials: Not known.
- (3) Losses: Principle energy losses occur as radiation from the gasifier, latent heat lost in condensers, energy expended to pulverize the coal, electricity and/or steam used to power equipment, and the latent heat of the product gases and by-products.

(e) Data Sources

- (1) Klass, D.L., and Chambers, W.C., 1976, A comparison of the net energy production ratios of integrated systems supplying natural gas and SNG from coal, paper presented at the 171st National Meeting of the American Chemical Society, New York, NY, 24 p.
- (2) Melcher, A.G., et.al., 1976, Net energy analysis: an energy balance study of fossel fuel resources: Golden, CO., Colorado Energy Research Institute, 225 p.

Module Energy Summary

(1) Principal Energy Input

Type: New Mexico subbituminous coal
Quantity, units: 10,000 tons/day
Btu/unit: 8800 Btu/lb
Btu input: 7333 x 10^6 Btu/hour

(2) Principal Energy Loss

2526 x 10^6 Btu/hour

(3) Principal Energy Output

Type: 954 Btu/scf gas	Liquid Byproducts
Quantity: 4125 x 10^6 Btu/hour	657 x 10^6 Btu/hour

Type: Electricity
Quantity: 25 x 10^6 Btu/hour

(4) Process Efficiency

65.6 %

(5) Principal Energy to be used within Process Boundary

Assumed to be none, but electricity is available.

6.7.4 In Situ Coal Gasification

Discussion of Process

In situ coal gasification is being developed to produce gases from coal seams that are too deep and/or thin or are at too steep of an angle to be mined economically. For in situ gasification, the coal is not mined but, rather, it is gasified underground in its natural position. The product gases can be low-Btu (100-300 Btu/scf) if air is used for gasification or they can be medium-Btu (300-60 Btu/scf) if oxygen is used. As with aboveground processes, the medium-Btu gases can also be converted to high-Btu gases by methanation.

The in situ gasification process is treated as one module with two elements in this handbook. The first element involves drilling wells into the coal seam from the surface. Some wells are used to introduce air, steam, and/or oxygen into the coal while the other wells are used to withdraw the product gases from the coal seam. The second element, gasification, consists of several steps and processes.

Several types of in situ coal gasification processes are now being developed. The type of coal, the depth and thickness of the coal seam, and the orientation of the seam all determine which in situ process should be used. In situ coal gasification can be classified into four basic categories: 1) linked vertical well, 2) packed bed, 3) longwall generator, and 4) steeply dipping beds.

The linked-vertical-well process consists of drilling many wells to the bottom of a coal seam. These wells are then "linked" by igniting the coal at the bottom of some wells and forcing air at high pressures into the seam from other wells. The ignited coal slowly burns toward the air injection wells until a burned-out channel (a "link") is established between the wells. When the flame front reaches the injection wells, the direction of air flow is reversed (air injection wells become gas recovery wells, and vica versa) and the gasification process is initiated. The gasification reactions are essentially the same as for aboveground processes.

The packed-bed process is very similar to the linked-vertical-well process in that wells are drilled from the surface and are then linked together. The major differences are that the packed-bed process incorporates the following: 1) explosives are used to fracture the coal seam and, thus, enhance its permiability, 2) oxygen is normally used rather than air, and 3) the coal bed is ignited near the top and the flame front progresses toward the bottom where the product gases are removed. This method is proposed for higher rank coals or for those coal seams that occur at greater depths.

The longwall-generator process uses directionally drilled wells that begin at the surface, curve until they pass horizontally through the coal seam for long distances, and return to the surface (often by a vertical well that intercepts the horizontal well). The wells lie in parallel rows, with the gasification reaction occuring between the wells. This method is primarily proposed for thin seams of Eastern bituminous coals.

Lastly, the steeply dipping bed gasification process is used for coal seams that are inclined at steep angles (i.e., steeply dippling). This method

utilizes air injection wells that are drilled to the bottom of a dipping coal seam and gas production wells that are located near the top of the seam.

Module Elements and Data

The first element for the in situ coal gasification module consists of drilling the wells prior to the actual gasification process. The values in this handbook are for the linked-vertical-well process, but are also probably reasonable values for the packed-bed and the steeply-dipping bed processses. However, these handbook values should not be used for the longwall-generator method because the very difficult process of directional drilling must be used for this method. If 4-in-diam wells are drilled to a depth of 415 ft, the estimated drilling time is one to two days, with an average fuel consumption of 140 gal per well (approximately 1/3 gal of fuel per foot of depth). For a 30-ft thick coal seam, a total of 160 wells must be drilled to produce 3520 x 10^6 Btu/m for 20 years. Hence, the total fuel consumed by the drilling rigs will be 224,000 gal and the annual consumption will be 11,200 gal/yr (1400 x 10^6 Btu/yr).

The second element of this module, gasification, consists of two distinct steps and several different operations. For an air-injected linked-vertical-well process, the gasification process consists of first linking the wells (step 1) and then reversing the air flow and gasifying the coal (step 2). For this handbook, the average energy required to compress the air for both steps is assumed to be 242 x 10^6 Btu/hr to produce 3520 x 10^6 Btu/m of low-Btu gas. This value, however, is highly variable depending on the depth, thickness, and porosity of the coal seam. In particular, the energy required for linking the wells can vary by a factor of 15. Thus, the air compression portion of the process specified in this handbook can vary from approximately 60 x 10^6 to 710 x 10^6 Btu/hr. If an air separation plant is used to produce oxygen for the gasification reaction, these energy consumption values can reasonably be expected to be even higher.

In addition to the air compression (or oxygen production) operation of the process, all in situ gasification methods require a gas cleanup facility. The gas cleanup operation involves removing particulates, tars and oil, sulfur compounds, and some carbon dioxide from the raw product gases. This portion of the process requires relatively little energy.

The greatest inefficiency of in situ gasification processes results from incomplete reaction of all the coal. A portion of the coal, approximately 20%, does not undergo complete gasification and, therefore, remains in the ground as a unrecovered resource. Additionally, some of the heating value of the coal is consumed in the gasification process to provide the necessary heat for the reactions.

The heating value of low-Btu gases is such that they cannot be economically transported over any great distances. Hence, all air-blown in situ coal gasification processes must incorporate a consumer such as anindustrial boiler or electrical power generating facility in close proximity to the gasification site. However, for the module in this handbook, the end user is not within the module boundary.

The assumptions and appropriate data for both elements, well drilling and gasification, are presented in Table 6.13. The following data are presented for an air-blown linked-vertical-well process for a particular type of coal, at a particular depth, and a particular seam thickness. Therefore, the data should be used only as an example of the methodology to be used for net energy analysis of an in situ coal gasification process. Because the values are so site specific and process specific, only data from the developer should be used for evaluation of a particular project.

TABLE 6.13

Module: In Situ Coal Gasification by the Linked-Vertical-Well Process to Produce Low-Btu Product Gases

Element 1: Well Drilling

(a) Equipment, facilities:

Four drilling rigs
Well casing
(Support facilities, such as buildings, are included in Element 2)

(b) Assumptions:

(1) Annual low-Btu gas production rate is 28.2 x 10^{12} Btu/yr (3520 x 10^6 Btu/hr).
(2) Well depth is 415 ft which requires 2 days and 140 gal of fuel to drill each well.
(3) Well diameter is 4 in.
(4) Coal seam thickness is 30 ft.
(5) Coal heating value is 10000 Btu/lb.
(6) Wells are spaced 150 ft apart in a square pattern.
(7) The theoretical number of wells needed per year is 64, but an allowance of 25% is added for well pluggage. Thus, 80 wells must be drilled per year.
(8) Fuel for the drilling rigs is valued at 125,000 Btu/gal.

(c) Guidelines for data:

(1) For wells of other depths, fuel consumed is approximately 1/3 gal per foot.
(2) Wells of diameters other than 4 in. require the same amount of fuel (i.e., no economies of diseconomies of scale).
(3) Annual fuel consumption is linear with the number of wells to be drilled each year.
(4) Data is for vertical wells only.

Equations:

(annual fuel consumption, gal)=(1/3 gal)(well depth, ft.)
(no wells per year)
(Btu consumption) = (fuel consumption, gal)(125,000)

(NOTE: As an indication of how variable the energy consumption can be for this element, Reference 2 specifies that 6400 wells must be drilled every year to produce 1000 MW of electricity from a 5-ft thick coal seam. Drilling this many wells to a depth of 2000 ft would require 4.3 x 10^6 gal of fuel per year - 380 times as much as assumed in this handbook. Additional, over 300 drilling rigs would be required, rather than 4 as was assumed for this module.)

TABLE 6.13

Continued

(d) Data:

(1) Direct Energy:
Diesel fuel = 1400 x 10^6 Btu/yr
(No other direct energy)
(2) Material:
Four drilling rigs = $400,000 (1974)
33,200 ft of 4-in-diam well casing
(3) Losses:
Negligible losses of the principle energy, coal, occur due to drilling the wells. Fuel requirements for the drilling rigs is 1400 x 10^6 Btu/yr.

(e) Data Sources:

(1) Frabetti, Alton Jr., Jr., et.al., 1975, A study to develop energy estimates of merit for selected fuel technologies: East Sandwich, Mass., Development Sciences, Inc., 376 p.
(2) Edgar, T.F., 1977, A revised economic study of in situ coal gasification of Texas lignite, a paper presented at the 2nd annual in situ energy recovery technology conf.: Albuquerque, N.M.

Element 2: Gasification

(a) Equipment, facilities:

Air compressors
Air distribution piping
Gas collection piping
Gas cleanup (Benfield process plus claus sulfur plant)
Buildings

(b) Assumptions:

(1) Energy usage is based on an air-blown linked-vertical-well coal gasification process.
(2) Annual gas production rate is 28.2 x 10^{12} Btu/yr.
(3) Project life is 20 years requiring 1080 x 10^6 ft^3 of coal resources.
(4) Coal heating value is 1400 Btu/lb with up to 5.0% sulfur.
(5) Raw product gas cleanup is accomplished with a Benfield process and a Claus sulfur plant.
(6) By-product sulfur has no energy value.
(7) Electricity required by the air compressors is valued at 3413 Btu/Kwh.

TABLE 6.13

Continued

(8) A process to consume the product gases is not included in the module.
(9) No economies or diseconomies of scale are assumed.
(10) Gas temperature is 250°F, thus contributing very little to the heating value of the gases.
(11) Energy for site preparation is assumed to be negligible.
(12) None of the product gases leak from the producing zone.

(c) Guidelines for data:

(1) Data are for an air-blown linked-vertical-well process only.
(2) Data are for only for the coal as specified.
(3) Data may be multiplied by a linear factor based on Btu/yr of gas produced relative to 28.2 x 10^{12} Btu/yr.

(d) Data:

(1) Direct Energy:

Electricity = 242 x 10^6 Btu/hr for air compression
Other direct energy consumption is negligible

(2) Materials:

Piping = \$11 x 10^6 (1974)
Gas purification = \$9 x 10^6 (1974)
Air compressors = \$25 x 10^6 (1974)

(3) Losses:

Approximately 20% of the heating value of the coal may be assumed to be lost as an unrecovered resource. An additional 15% of the coal heating value is consumed by the gasification reactions. The electricity used by the air compressors results in Direct Energy consumption of 242 x 10^6 Btu/hr. (Depending on the type of coal and the thickness and depth of the coal seam, electricity consumption can vary by a factor of 15.) Negligible energy is required for the gas purification process and the supporting facilities.

(e) Data Sources:

(1) Frabetti, Alton Jr., Jr., et.al., 1975, A study to develop energy estimates of merit for selected fuel technologies: East Sandwich, Mass., Development Sciences, Inc., 376 p.
(2) Edgar, T.F., 1977, A revised economic study of in situ coal gasification of Texas lignite, a paper presented at the 2nd annual in situ energy recovery technology conf.: Albuquerque, N.M.

TABLE 6.13

Continued

Module Energy Summary

(1) Principal Energy Input
Type: Wyoming subbituminous coal
Quantity, units: 5197.2 tons/day
Btu/unit: 10,000 Btu/lb
Btu input: 433 x 10^6 Btu/hour

(2) Principal Energy Loss

821 x 10^6 Btu/hour + 1083 x 10^6 Btu/hour (unrecovered resource)

(3) Principal Energy Output

Type: Low-Btu gas
Quantity: 3510 x 10^6 Btu/hour

(4) Process Efficiency

81.0% or 64.8% including unrecovered resource

(5) Principal Energy to be used within Process Boundary

None

(11) Reserve Recovery

Efficiency: 80.0%

	ft^3	Btu
Reserve:	1080 x 10^6	868.0 x 10^{12}
Unrecovered Reserve:	216 x 10^6	173.6 x 10^{12}

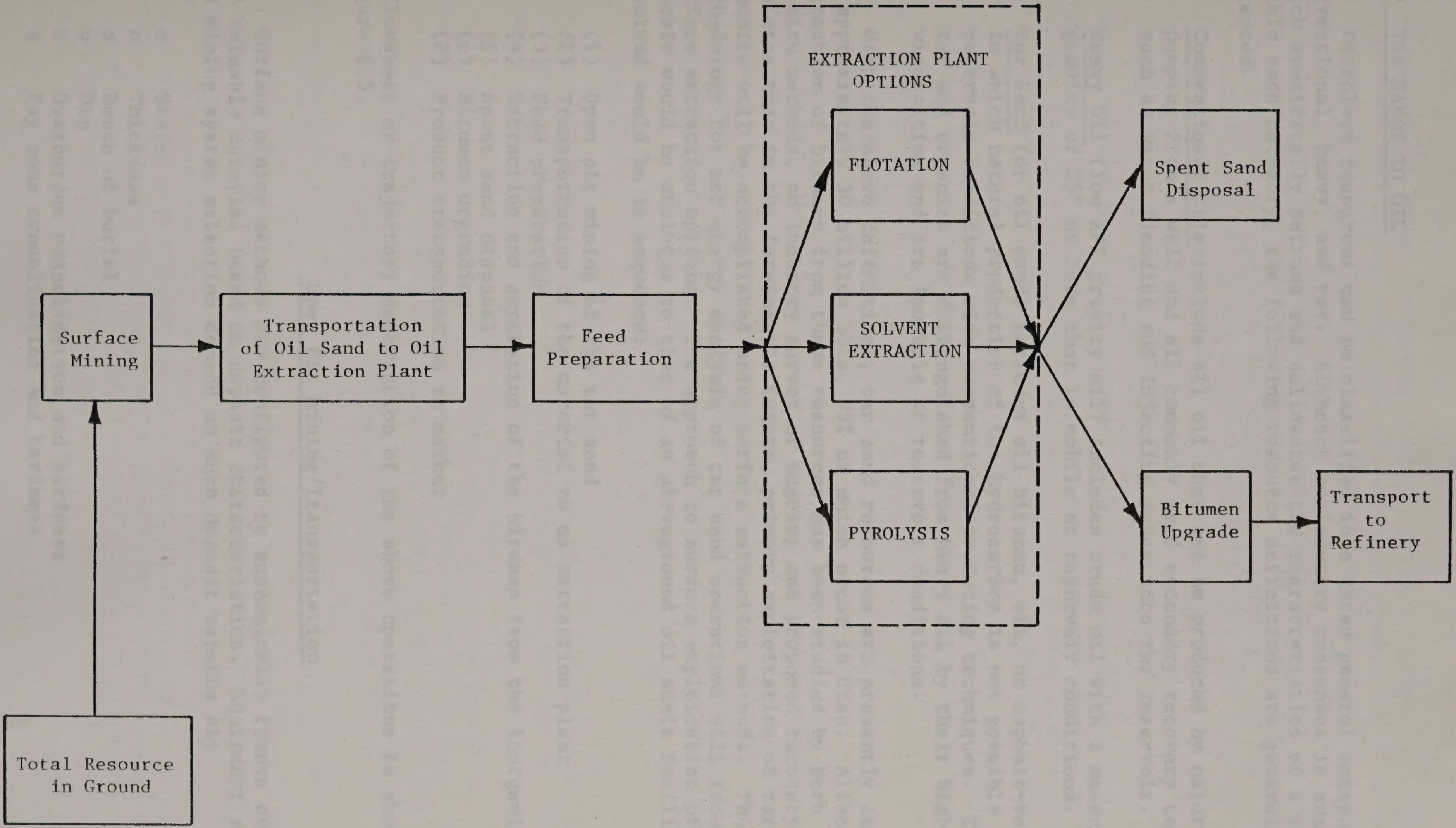


FIGURE 6.5
Tar Sands Processing

6.8 TAR SANDS TO OIL

Petroleum resources can be classified into three general categories: conventional, heavy, and tar. Although no industry consensus is available which specifically defines and delineates the characteristics of a reservoir within each category, the following resource definitions are generally accepted.

Conventional Oils include all oil that can be produced by natural flow or pumping from a well and all commonly used secondary recovery techniques, such as water flooding and injecting gases into the reservoir.

Heavy Oil (low API gravity oil) includes crude oil with a measured API gravity of 25° or less that is mobile at reservoir conditions.

Tar Sand (or oil sand) includes all bitumen, oil, or asphalt-bearing rock in which natural production of the hydrocarbon is not possible at reservoir conditions with conventional producing techniques. Typically tar and organics are distinguished from heavy oil by their higher viscosities and are immobile at reservoir conditions.

With the above definitions, tar sand resources are presently estimated to be approximately 30 billion bbls, 95% of which occur in Utah. Although extraction of bitumen from these resources has been studied by both surface and in situ methods, an industry survey of ongoing and proposed recovery programs indictes that in the foreseeable future, primary exploitation of tar and deposits will be accomplished using surface extraction methods. Thus methodology for net energy analysis of tar sand operations will focus on surface extraction options. The approach to surface exploitation of a tar sand deposit would be anologus to that of an aboveground oil shale facility. Involved would be in sequence:

(1) Open pit mining of the tar sand
(2) Transportation of the material to an extraction plant
(3) Feed preparation
(4) Extraction and separation of the bitumen from the inorganic matrix
(5) Spent sand disposal
(6) Bitumen upgrading
(7) Product transportation to market

A flowsheet or trajectory description of the above operations is shown in Figure 6.5.

Open Pit Mining/Transportation

Surface mining methods are configured to economically remove overburden and valuable material based on deposit characteristics. Equipment selection and mining system selection depend on such deposit aspects as:

- Shape
- Thickness
- Depth of burial
- Dip
- Overburden consolidation and hardness
- Pay zone consolidation and hardness

Proper mining method selection is site specific. However, the general characteristics of the deposit in the western region amenable to surface extraction will probably use a modified terrace pit mining method. Overburden and pay zone thickness, and material competence will probably require drilling and blasting of the rock followed by shovel loading into trucks for haulage to the extraction plant or intermediate conveyors. Some strip mining of the overburden prior to pit development may also be employed. Net energy analysis of the mining transporation module would be similar to that discussed to evaluate open pit oil shale mining.

Bitumen Extraction

Feed to a surface extraction facility will probably contain 8 to 12 wt percent bitumen. To be competitive, a tar sand operation must selectively extract the bitumen from this material and convert it into a marketable petroleum product.

Various methods are available to concentrate or extract bitumen. The three general approaches receiving the most industry investigation are:

- o Flotation
- o Solvent extraction
- o Pyrolysis

These methods may be used exclusively or in sequential combination. For example, companies have proposed using flotation followed by solvent extraction or pyrolysis. General descriptions of each of the above extraction procedures are presented in the following sections. Proposed processes may vary in detail; however, they will most likely incorporate the major aspects that are discussed.

Feed Preparation

Tar sand material received from the mine will be placed in intermediate storage prior to being fed to the extraction circuit. Storage may take place in open stockpiles and/or enclosed bins.

The material will then be reclaimed using a transfer device and fed to a comminution circuit. Some type of crushing operation will be involved which may include multiple stages with inter stage transfer and classification operations. If the extraction circuit requires a relatively small feed size, grinding of the crushed product may be necessary.

Flotation Module

As configured, Feed from the preparation plant is subjected to high shear attrition scrubbing to disengage the bitumen from the inorganic matrix. The scrubber discharge continues to a primary flotation circuit where liberated bitumen is concentrated in a froth product. Primary attrition scrubbing and primary flotation may be performed at an elevated temperature. Flotation nonfloat or tailings is sent to a scavenger flotation to recover bitumen which is not sufficiently liberated. The scavenger concentrate is recycled to the attrition scrubber for additional treatment. Scavenger tailing is sent to disposal.

The primary flotation concentrate is treated to reject water and entrained inorganic material. This may involve the use of a diluent solvent to reduce bitumen viscosity. After cleanup, the solvent, if employed, would be separated from the bitumen by simple distillation and recycled. The bitumen concentrate would then be either upgraded directly or used as ffed to a pyrolysis module or solvent extraction. Concentrate cleanup tailing would be disposed.

With regard to general energy flow, in addition to the normal primary energy and energy associated with materials, equipment and electrical requirements, energy associated with steam heating the slurry and energy inherent in any solvent makeup must be accounted as input. Of note is the energy loss associated with unrecovered bitumen and solvent reporting with the tailing stream.

From the primary energy stream a portion of the concentrated bitumen could be used for steam generation. If so employed, the energy balance must account for this recycle.

Solvent Extraction Module

Tar sand feed either after preparation or as flotation concentrate is contacted with a solvent to solubilize all or selected components of the contained bitumen. After extraction, the slurry is subjected to counter current liquid solid separation. The solid phase consisting of residue sand is heated in some form to recover entrained solvent and solubilized bitumen which is recycled. The washed sand is then sent to disposal. The bitumen loaded solvent is treated by distillation to recover solvent for recycle. The bitumen product obtained is upgraded and/or marketed.

Shown along with the common energy flow associated with the primary energy stream and materials, equipment, and electrical consumption, energy flows specific to the solvent extraction module would include:

Energy Inflow

- Energy inherent in makeup solvent
- Heat (steam) to solvent recovery unit operations

Energy Loss

- Systems heat losses
- Sensible heat, unrecovered bitumen and unrecovered solvent in tailing stream

Energy Outflow

- Sensible heat and unrecovered solvent in bitumen primary energy stream

If a portion of the primary bitumen product is employed to generate process stream, adjustments to the module energy balance must be made accordingly.

Pyrolysis Module

Prepared run-of-mine tar sand or flotation concentrate is subjected to pyrolysis which converts bitumen into vapor phase oils, gases and coke. The oil and gases are carried off and separated into final products which are upgraded or marketed directly. The coke which is deposited on the inorganic matrix will generally undergo combustion to provide all or a major proportion of the process heat requirements. Depending upon the type of method, all or portions of the combustion gases and/or the heated sands are recycled to provide heat to the pyrolysis operation. Ultimately the combustion gas products and sand residue is rejected from the pyrolsis module.

Energy flows specific to a pyrolysis module include:

Energy Inflow

- Auxilary fuel to the combustion unit as required

Energy Loss

- Combustion gas discharge
- Sensible heat contained in disposed sand
- Systems heat loss

Energy Outflow

- Sensible heat contained in liquid and gas products

Portions of the liquid and gas products could be used for all or part of the auxilary fuel requirements. Combustion gas discharge may also be used as fuel to a CO boiler.

Consistent with the previously discussed modules, the energy balance for the pyrolysis step would include primary energy streams and energy inherent in materials equipment and electrical consumption.

Residue Sand Disposal

Because only approximately 10 weight percent of the tar sand feed is bitumen, the major portion of the material is disposed after extraction. The problems, concerns and cost, both energy and economic, would be similar to any surface mining operation which only extracts a minor portion from the material. The methods are anologus to disposal of spent shale from a surface retort operation which is discussed in detail in Section 4.

Bitumen Upgrading/Transportation

A raw bitumen product has similar detrimental characteristics as raw shale oil such as:

- High viscosity
- High pour point
- Excessive sulfur and nitrogen content and, in addition, a high asphalt content

Some of these aspects may be improved via a pyrolysis extraction method. However, sulfur and nitrogen contents would still detract from the value of the product.

Thus to enhance its marketability, a bitumen concentrate will probably have to be upgraded. Although specific process conditions may be different, upgrading schemes will be similar to those described for shale oil in Section 4. Transportation of the refined products would also involve the options discussed for upgraded shale in Section 4.

Data

A thorough literature search and contacts with industry reveal that data on energy inputs and outputs are not available, because no tar sand operations have actually been designed, constructed or operated. Hence, it is impossible to provide any realistic data for this standard module. Should this handbook be used in a study involving a proposed tar sands operation, it will be necessary for the analyst to obtain data from the proposer of the action.

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(10) Grand Total, External Energy Inputs (8)+(9):

Crude Oil	Natural Gas	Coal	Hydropower	Nuclear	Other Energy

(9) Energy in Materials, by type of energy, as resources in ground.

Material	Quantity, Units	Crude Oil	Natural Gas	Coal	Hydropower	Nuclear	Other Energy
	Sum, item (9):						

Grand Total, (9): ____________

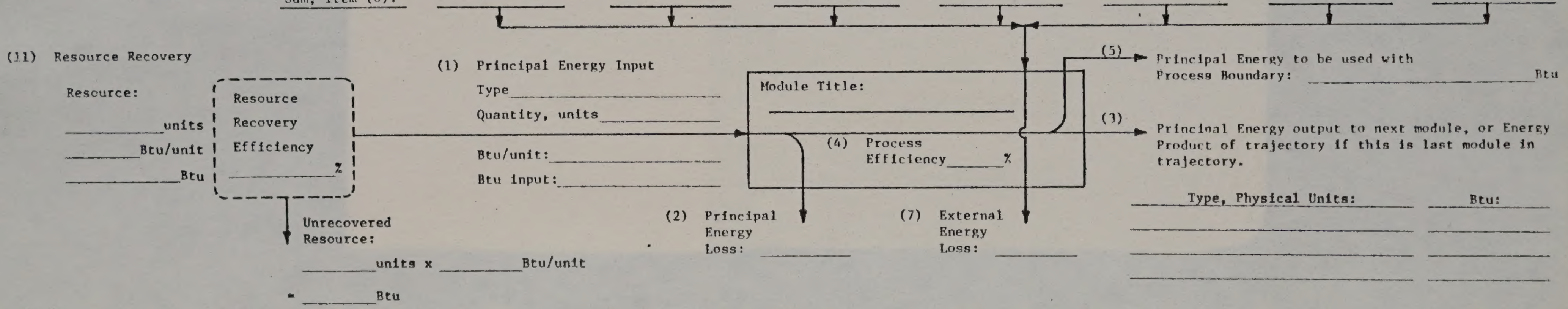
(8) Total External Energy as Resources in Ground:

Direct Energy type:	Crude Oil	Natural Gas	Coal	Hydropower	Nuclear	Other Energy
Electric, Off-site						
Electric, On-site						
Gasoline						
Diesel						
Natural Gas						
Other						
Other						
Sum, item (8):						

Grand Total, (8): ____________

(6) Direct External Energy in total Btu's for each element by energy type, and as sum of each energy type for all elements.

Elements:	Elec., Off-site	Elec., On-site	Gasoline	Diesel	Natural Gas	Other	Other
Sum, item (6):							



(11) Resource Recovery

Resource:

____________units

__________Btu/unit

______________Btu

Resource Recovery Efficiency ____________%

Unrecovered Resource:

__________units x __________Btu/unit

= __________Btu

(1) Principal Energy Input

Type____________________

Quantity, units____________________

Btu/unit:____________________

Btu input:____________________

Module Title:

____

(4) Process Efficiency________%

(2) Principal Energy Loss: __________

(7) External Energy Loss: __________

(5) Principal Energy to be used with Process Boundary: ____________________Btu

(3) Principal Energy output to next module, or Energy Product of trajectory if this is last module in trajectory.

Type, Physical Units:	Btu:

FIGURE ______

Module Data for ______________________________

Scaling Factor for Standard Module____________Standard Module __________